

T.R
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NANOTECHNOLOGY

**PHYSICAL PROPERTIES OF POLYVINYLIDENE
FLUORIDE NANOFIBERS (PVDF NF) FILLED WITH
NANOPARTICLE FILLER FOR SENSOR APPLICATION**

WAFAA ABDALLAH SULIMAN ABKAR
A THESIS SUBMITTED FOR THE DEGREE OF
MASTER OF SCIENCE
DEPARTMENT OF NANOSCIENCE AND
NANOENGINEERING

GEBZE
2023

T.R
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NANOTECHNOLOGY

**PHYSICAL PROPERTIES OF
POLYVINYLIDENE FLUORIDE
NANOFIBERS (PVDF NS) FILLED WITH
NANOFILLERS FOR SENSOR
APPLICATION**

WAFAA ABDALLAH SULIMAN ABKAR
A THESIS SUBMITTED FOR THE DEGREE OF
MASTER OF SCIENCE
DEPARTMENT OF NANOSCIENCE AND
NANOENGINEERING

THESIS SUPERVISOR
PROF. DR. FİKRET YILDIZ

GEBZE
2023

T.C
GEBZE TEKNİK ÜNİVERSİTESİ
NANOTEKNOLOJİ ENSTİTÜSÜ

SENSÖR UYGULAMASI İÇİN NANO
DOLGULARLA DOLDURULMUŞ POLİVİNİLİDİN
FLORÜR NANOLİFLERİN (PVDF NS) FİZİKSEL
ÖZELLİKLERİ

WAFAA ABDALLAH SULIMAN ABKAR
YÜKSEK LİSANS DERECEŚİ İÇİN SUNULMUŞ
TEZ
NANOBİLİM VE NANOMÜHENDİSLİK
BÖLÜMÜ

TEZ DANIŞMANI
PROF. DR. FİKRET YILDIZ

GEBZE

2023



YÜKSEK LİSANS JÜRİ ONAY FORMU

GTÜ Fen Bilimleri Enstitüsü Yönetim Kurulu'nun/...../..... tarih ve
/..... sayılı kararıyla oluşturulan jüri tarafından/...../..... tarihinde tez savunma
sınavı yapılan'ın tez çalışması
.....Anabilim Dalında YÜKSEK LİSANS tezi olarak kabul
edilmiştir.

JÜRİ

ÜYE

(TEZ DANIŞMANI)

:

ÜYE

:

ÜYE

:

ONAY

Gebze Teknik Üniversitesi Fen Bilimleri Enstitüsü Yönetim Kurulu'nun
...../...../..... tarih ve/.....sayılı kararı.

İMZA/MÜHÜR

SUMMARY

Polymer-based nanocomposites have attracted a lot of interest because of their outstanding mechanical and electrical properties in recent years. PVDF is a semi-crystalline polymer that exists in four crystal forms known as α , β , γ and δ crystal phases. In addition to its ferroelectric and piezoelectric properties, polyvinylidene fluoride (PVDF) is a lightweight, easily processed, and flexible material. It contains a high percentage of β crystal phase compared to the other structural phases, which is the reason for spontaneous polarization due to ferroelectricity and piezoelectricity. The PVDF's β -phase is responsible for remarkable electroactive properties that can be obtained by several methods such as mechanical stretching, annealing, and electric field poling.

Numerous studies have demonstrated that the β -phase can be improved by the addition of nano-fillers such as clay, barium titanate, a hydrated ionic salt, silver nanoparticles, carbon nanotubes (CNTs), nanowires, zinc oxide, and CNTs. Nanofillers could also enhance dielectric and ferroelectric properties that are being included in PVDF. In order to produce β phase in PVDF with nano-fillers efficiently, electrospinning technique is used which combined electrical poling and mechanical stretching by converting PVDF into nanofiber.

In this thesis, the surface morphology of the PVDF NFs was investigated by scanning electron microscope (SEM), and the dielectric properties of nanoparticle-filled PVDF nanofibers were characterized using an LCR meter operating in the 10 MHz-240GHz frequency range. Temperature dependence of Capacitance of PVDF nanofibers -ferrite nanofiller composites is also investigated.

PVDF nanofibers-ferrite nanofiller composites were characterized below their curie temperature and showed strong frequency dependence of capacitance change with temperature.

Keywords: Polyvinylidene fluoride (PVDF), β phase, Dielectric properties of PVDFs, Temperature sensor.

ÖZET

Polimer bazlı nanokompozitler son yıllarda üstün mekanik ve elektriksel özelliklerinden dolayı büyük ilgi görmüştür. PVDF, α , β , γ ve δ kristal fazları olarak bilinen dört kristal formda bulunan yarı kristal bir polimerdir. Ferroelektrik ve piezoelektrik özelliklerinin yanı sıra poliviniliden florür (PVDF) hafif, kolay işlenebilir ve esnek bir malzemedir. Diğer yapısal fazlara kıyasla yüksek oranda β kristal fazı içerir, bu da ferroelektriklik ve piezoelektriklik nedeniyle kendiliğinden polarizasyonun nedenidir. PVDF'nin β -fazı, mekanik germe, tavlama ve elektrik alanı kutuplaması gibi çeşitli yöntemlerle elde edilebilecek olağanüstü elektroaktif özelliklerden sorumludur.

Çok sayıda çalışma, β -fazının kil, baryum titanat, hidratlı iyonik tuz, gümüş nanopartiküller, karbon nanotüpler (CNT'ler), nanoteller, çinko oksit ve CNT'ler gibi nano dolgu maddelerinin eklenmesiyle geliştirilebileceğini göstermiştir. Nano dolgu maddeleri ayrıca PVDF'de bulunan dielektrik ve ferroelektrik özellikleri de geliştirebilir. PVDF'de nano dolgularla verimli bir şekilde β fazı üretmek için, PVDF'yi nanofiber haline dönüştürerek elektriksel kutuplama ve mekanik germeyi birleştiren elektro eğirme tekniği kullanılmıştır.

Bu tezde, PVDF NF'lerin yüzey morfolojisi taramalı elektron mikroskobu (SEM) ile araştırılmış ve nanopartikül dolgulu PVDF nanofiberlerin dielektrik özellikleri 10 MHz-240GHz frekans aralığında çalışan bir LCR metre kullanılarak karakterize edilmiştir. PVDF nanolifleri-ferrit nanodoldurucu kompozitlerinin kapasitansının sıcaklığa bağımlılığı da araştırılmıştır.

PVDF nanolifleri-ferrit nanodoldurucu kompozitleri, sertleşme sıcaklıklarının altında karakterize edildi ve sıcaklıkla kapasitans değişiminin güçlü frekans bağımlılığını gösterdi.

Anahtar Kelimeler: Poliviniliden florür (PVDF), β fazı, PVDF'lerin dielektrik özellikleri, Sıcaklık sensörü.

ACKNOWLEDGMENTS

All praise to almighty Allah, without His blessings I won't be able to make it until this point. I want to dedicate this work to my parents, Hawaa Abdelnour and Abdallah Suliman, who have always showed me their love, and support from my home country.

I would like to express my sincere gratitude and appreciation to my dissertation supervisor, Prof. Dr. Fikret YILDIZ, for his encouragement, guidance, and support throughout my study. I would like to express my gratitude and special appreciation to Asst. Prof. Dr. Maksut MAKSUTOĞLU for his guidance and kind support to learn many things in my master's career. I also would like to thank Prof. Dr. Mustafa EGINLIGIL and his team for fabricating the samples investigated in this thesis.

I also would like to thank Assoc. Prof. Dr. Sadiye VELİOĞLU, Assist. Prof. Osman EKSİK and Assoc. Prof. Dr. Hatice ONAY for their kindness, support, and encouragement

I also would like to thank research assistants Ahmet Musap MERT, Okan ÖZDEMİR, Onur Alp AKSAN and Hatice Yasemin İSKENDER for helping me do the experimental characterization.

Finally, I would like to express my sincere thanks to my friends, Tuğba BAYSAL, Hasan TOPAÇLI, Şirin MASSOUMILARI and Mütessir TEMEL, for their encouragement and support.

TABLE OF CONTENTS

SUMMARY	v
ÖZET.....	vi
ACKNOWLEDGMENTS	vii
TABLE OF CONTENTS	viii
LIST OF ABBREVIATIONS AND ACRONYMS	x
LIST OF FIGURES	xii
LIST OF TABLES	xiv
1. INTRODUCTION.....	1
2. NANOFIBERS AND THEIR FABRICATION TECHNIQUES.....	1
2.1. Definition Of Nanofibers.....	1
2.2. Properties Of Nanofibers	2
2.3. Nanofibers Production Techniques.....	3
2.3.1. Conventional Methods.....	4
2.3.1.1. Template Synthesis.....	4
2.3.1.2. Phase Separation.....	4
2.3.1.3. Drawing.....	5
2.3.2. Modern Methods.....	6
2.3.2.1. Electrospinning:.....	6
3. POLYVINYLDENE FLUORIDE(PVDF).....	8
4. POLYVINYLDENE FLUORIDE(PVDF) TEMPERATURE SENSOR.....	11
4.1. PVDF Temperature Sensor Principal Work:	13
4.2. PVDF Temperature Sensor Applications	13
4.2.1. PVDF Temperature Sensor In Medical Filed:	14
4.2.2. PVDF Temperature Sensor In Electronic Skin Application	14
5. FUNDAMENTALS OF DIELECTRIC THEORIES.....	15
5.1. Dielectrics And Insulating Materials	15
5.1.1. Electric Dipole Moment.....	16
5.1.2. Electric Field(E))	16
5.1.3. Dielectric Constant(ϵ_r)	17
5.2. Classification Of Dielectric Materials	18
5.3. Ferroelectric Materials.....	19

5.3.1. Phase Transitions Of Ferroelectric Material	21
5.3.1.1. Phase Transitions Of The First Order.....	22
5.3.1.2. Phase Transitions Of The Second Order	22
5.3.2. Spontaneous Polarization.....	24
6. MATERIALS AND METHOD	25
6.1. Materials	25
6.2. PVDF NFs And PVDF-Ferrite nanofiller NFs Preparation	25
6.3. Method:.....	26
7. RESULTS AND DISCUSSION	27
7.1. Structural Properties	27
7.2. Dielectric Properties Of PVDF-IP	30
7.2.1. Temperature Effect on Capacitance of PVDF(NFs)- Ferrite Nanofiller With Constant Frequency	30
7.2.2. Frequency effect on Capacitance of PVDF- ferrite nanofiller... ..	32
8. CONCLUSION	35
REFERENCES.....	36
BIOGRAPHY.....	38

LIST OF ABBREVIATIONS AND ACRONYMS

<u>Abbreviations and Acronyms</u>	<u>Explanations</u>
A	: Alpha
AC	: Alternating current
Ba	: Barium
B	: Beta
C	: Capacitance
Δ	: Delta
ϵ_r	: Dielectric constant
DMF	: Dimethylformamid
DC	: Direct current
Q	: Electric Charge
μ	: Electric dipole moment
D	: Electric displacement
E	: Electric field vector
F	: Electric Force
EDS	: Energy-dispersive spectroscopy
fF	: Femto-Farad
FNf	: Firret nanofiller
Γ	: Gamma
IC_s	: Integrated circuits
μF	: Micro-Farad
Nf	: Nano-Farad
NFs	: Nanofiber
NP_s	: Nanoparticle
O	: Oxygen
ϵ_0	: Permeability of vacuum
pF	: Pico-Farad
P	: Polarization
PET	: Polyethylene terephthalate
PTFE	: Polytetrafluoroethylene

PVDF	:	Polyvinylidene fluoride
PVDF-TrFE	:	Polyvinylidene fluoride-trifluoroethylene
RTDs	:	Resistance temperature detectors
SEM	:	Scanning electron microscopy
P_s	:	Spontaneous polarization
A	:	Surface area
Σ	:	Surface charge density
CT	:	Temperature-dependent capacitance
D	:	Thickness
Ti	:	Titanium
TENG	:	Triboelectric nanogenerator
XRD	:	X-Ray diffraction

LIST OF FIGURES

<u>Figure No:</u>		Page
2.1:	Diameter and specific properties of nanofibers	1
2.2:	Possible structures and application areas of nanofibers	3
2.3:	Illustration of template synthesis method	4
2.4:	Illustration of phase separation method	5
2.5:	Illustration of drawing method	5
2.6:	Illustration of electro-spinning set-up.	6
3.1:	Schematic representations of the chain conformation for the α , β , and γ phases of PVDF	10
4.1:	A parallel-plate capacitor	17
4.4:	Orientation of permanent electric dipoles due to an external electric field. (A) In the absence of an electric field, (B) under the influence of an electric field, with no molecular interactions, and (C) under the influence of an electric field, with molecular interactions	19
4.5:	Interrelationship among piezoelectric, ferroelectric, pyroelectric, and dielectric materials. Ferroelectric materials have superior pyroelectric, piezoelectric, and dielectric properties than non-ferroelectric materials	21
4.6:	Potential for a good schematic	22
4.7:	Spontaneous polarization plots against temperature: (a) transition of the first order (b) transition of second order	23
4.8:	Hysteresis loop of ferroelectric material. (P-E)	24
6.1:	Characterization of the dielectric properties of PVDF-ferrite nanofiller by LCR meter	26
7.1:	PVDF- ferrite nanofiller nanofibers' surface morphology. PVDF with ferrite nanofiller that were made with various growth times is seen using scanning electron microscopy (SEM).	27

7.2:	EDS (energy-dispersive spectroscopy) of the PVDF-ferrite nanofiller NFs grown in 4 hours. The EDS spectra of PVDF- ferrite nanofiller NFs that were grown for four hours clearly show a Fe contribution.	28
7.3:	Temperature effect on Capacitance with constant frequency (50NHZ) of PVDF (NFs)- ferrite nanofiller that were prepared with different growth time. (a) PVFF(NFs)-50nm, (b)PVDF(NFs)-150nm, (c)PVDF(NFs)-290nm	31
7.4:	Frequency effect on Capacitance of PVDF (NFs)- ferrite nanofiller at constant temperature ($T= 26^{\circ}\text{C}$) and frequency range (10-240MHZ), (a) PVDF(NFs)-50nm, (b) PVDF(NFs)-150nm, and (c) PVDF(NPs)- 290nm.	32
7.5:	The sensitivity ($\Delta C/\Delta T$) of PVDF - ferrite nanofiller (a) PVDF (NFs)-50nm(b) PVDF(NFs) -150nm, (c) PVDFNPs)- 290nm	34

LIST OF TABLES

<u>Table No:</u>	Page
2.1: Comparison of conventional fibres, melt blown fibres and nanofibers	2
7.1: Composition of ferrite nanofiller, energy-dispersive spectroscopy (EDS).	29



1. INTRODUCTION

Our desire to observe and learn more about the world motivates the use of sensors. Sensors are used in all technological areas because of the growth of consumer electronics. Sensors convert information in the form of energy changes, such as optical, electrical, magnetic, biochemical energy, thermal, and mechanical, into another form of energy. For instance, the increase in temperature caused by the heat released by a disc brake could be used to obtain information about a vehicle's kinetic energy.

Sensors have a significant effect on our lives and are essential in many various application areas. A sensor is a device that can sense physical quantities (such as thermal, light, magnetic, mechanical, chemical, etc.) and transform them into other quantities, generally electrical.

Sensors can be classified based on their operating principle or the type of output signal they provide; however, sensors are frequently classified based on the kind of quantity they measure: light sensors, sound sensors, temperature sensors, electrical resistance sensors, distance sensors, pressure sensors, strain sensors, and so on. Sensors are frequently categorized according to their active behaviour into:

- o Active sensors: Active sensors transform input energy directly into output energy without external power.
- o Passive sensors: External power (excitation) is required for conversion.

Several significant criteria characterize sensor performance, including:

- 1- Accuracy: The maximum deviation between a sensor's measurement and the measurement's actual value.
- 2- Sensitivity: The ratio between the change in the input quantity and the change in the output signal to the transducer.
- 3- Calibration: The converter determines the output variable from the known input variable value.
- 4- Resolution: The smallest quantity that can be measured or the smallest input change that has a perceptible effect on the output.
- 5- Hysteresis: Identifies the existence of the sensor's "memory" effect, which might be impacted by its prior operational condition when the measurement uses the same value."

6- Response time: Time required to attain a specified percentage of the output signal's ultimate value.

7- Stability: the ability of a converter to maintain its operational properties over a long period (months or years).

The demand for stretchable and flexible strain and pressure sensors is rising due to the increasing number of applications in numerous sectors, including industrial, automotive, robotics, sports, biomedical, and medical. [1], as shown in Figure 1.2.

Strain sensors transform mechanical deformation into electrical impulses; therefore, they have recently sparked a lot of attention in advanced applications to create bodily-integrated electronic devices capable of sensing and analyzing human body motions and gestures in real time.

For example, These advanced systems can be immediately affixed to the skin (e.g., electronic tattoos) or garments (e.g., smart e-textiles) [2–4].

Motion state sensors in this context primarily concentrate on how the human body moves in activities like sports, walking, sleeping, and rehabilitation and to observe conditions that affect physiological movement.

Material selection plays an essential role in the development of sensors in order to guarantee the final device's complex functional properties, such as flexibility, excellent electrical properties, and low cost.

According to comprehensive research in the literature, nanomaterials are the most suited and promising alternatives to satisfy these demanding requirements.

Nanostructured materials are known as materials with at least one dimension in the 1- 100 nanometres range.

Consequently, the term "nanotechnology" refers to fields of engineering or the natural sciences in which nanometric phenomena are utilized to create, characterise, and realise novel, cutting-edge systems or devices.

The term "nanotechnology" first appeared in the 1960s after Richard Feynman's lecture "There's Plenty of Room at the Bottom," in which he described the ability to manipulate objects atom by atom. Material properties are size-dependent in the nanoscale; when one reaches the interatomic distance regime, surface effects can become dominating and quantum effects can become significant.

This results in significant modifications to the macroscopic mechanical, fluidic, electromagnetic, and thermodynamic laws in terms of mechanical properties, surface,

and interface forces, such as adhesion, capillary, and strain forces, becoming dominant at the nanoscale level. Additionally, a quantum mechanical phenomenon called tunnelling becomes dominant when it comes to electrical properties, which entirely alters the electronic properties of solids relative to their macroscopic surroundings. All the novel properties of nanoscale-scale materials enable novel and innovative applications. Due to their unique characteristics, particularly the high surface-to-volume ratio, nanostructured materials provide significant opportunities for developing flexible sensors that outperform conventional flexible sensors in terms of electrical and mechanical performance.



2. NANOFIBERS AND THEIR FABRICATION TECHNIQUES

2.1. Definition of Nanofibers

With the widespread use of nanoscience and nanotechnology, researchers have taken a keen interest in investigating the superior properties of nanoscale materials, especially nanofibers. Nanofibers are defined as fibres with a diameter between 1 and 100nm and a high specific surface area of up to 1000 m²/g [5]. Nanofibers can also be defined as nanomaterials with a diameter of less than 1µm (Figure 2.1) [6].

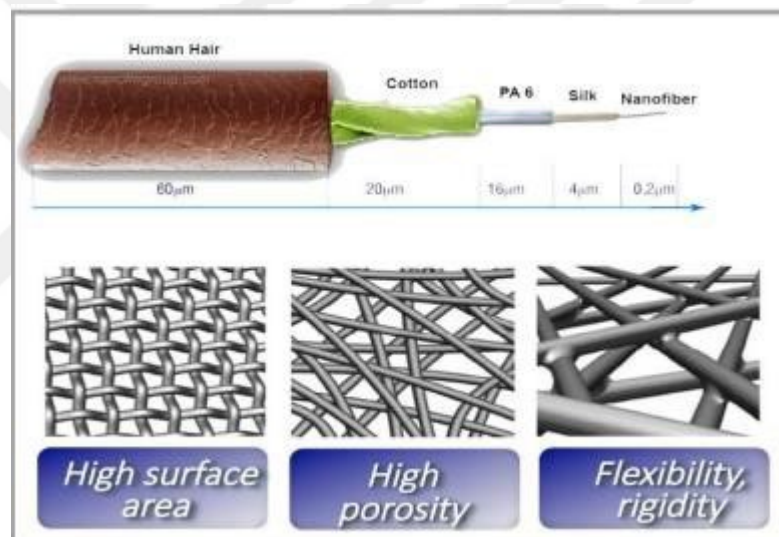


Figure 2.1: Diameter and specific properties of nanofibers.

It is known that nanofibers were first produced by William Gilbert (1544-1603). He had observed that when water was dropped on the dry surface and exposed to an electrical charge, the water turned into a cone shape, now known as the Taylor cone. Subsequently, most scientists and inventors such as Lord Rayleigh, Charles Vernon Boys, John Francis, and Anton Forman worked on this topic and pioneered the development of nanofiber electro-spinning. Subsequently, in 1995, Doshi and Reneker popularized electro-spinning [7]. Nanofibers are made from numerous organic and inorganic polymers such as polyacrylonitrile, polyvinyl alcohol copolymers, polymers with various additives, silica, nanoparticles, and others [8]. As already mentioned, nanofibers have excellent properties and are, therefore, still the most popular in many

fields of application. Every day, countless studies on nanofibers are published and applied in many new areas.

2.2. Properties of Nanofibers

Nanofibers have unique characteristics such as high specific surface area, high porosity (up to over 80%), low core weight, tiny pore size, ability to be incorporated into other media, and the ability to be fabricated into different structures.

Therefore, these fibres are recommended for a variety of applications [9], such as biomedical applications [10, 11], electrical and optical [8, 9], protective clothing [10, 11] and environmental applications (Figure 2.2) [12-14].

Table 2.1 compares conventional fibres, melt-blown fibres and nanofibers [4].

Table 2.1: Comparison of conventional fibres, melt-blown fibres and nanofibers [8].

Fibers	Fiber Diameter(μm)	Liner Density(dtex)	Specific Surface Area(m^2/g)
Conventional	10-40	1-30	ca. 0.2
Melt-Blown	1-5	ca. 0.01	ca. 2
Nanofibers	0.05-0.5	Ca. 0.0001	Ca. 20

The excellent specific surface area combined with the small fibre diameters allows the materials to interact with the environment quickly. For this reason, they are used in filters, membranes, wound dressings, chemical and biological protective clothing, energy storage devices and sensors [15].

Many new nanofibers have been recently prepared, including some support materials such as Au, Ag, TiO_2 , MgO , MnO_2 , Al_2O_3 , ZnO and Fe_2O_3 to obtain multifunctional nanofibers. In this way, the nanofibers acquire additional properties such as biodegradability, hydrophobicity, photocatalytic and electrical conductivity. As a result, they can be applied to fields like photocatalysis, biological sensing, capacitors, gas filtering, and energy generation/storage [16, 17].

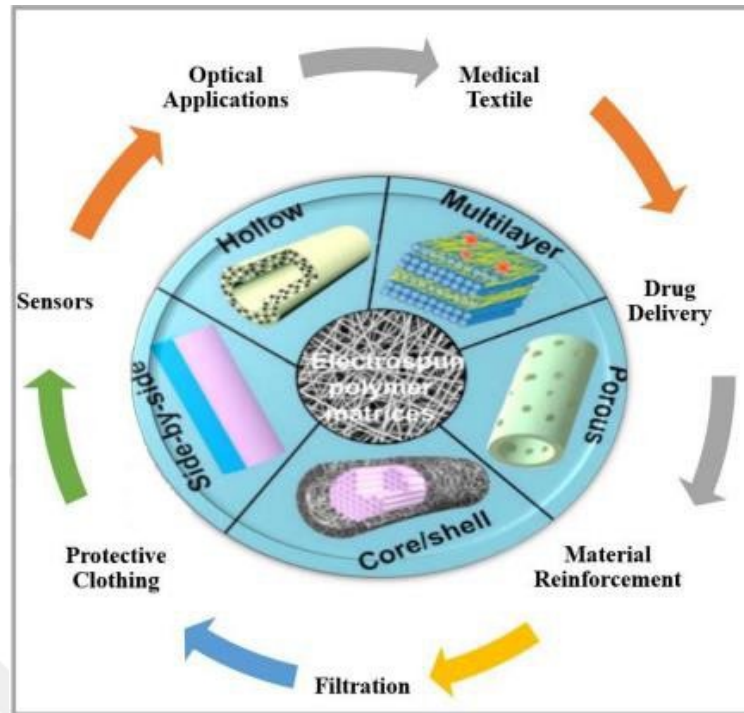


Figure 2.2: Possible structures and application areas of nanofibers.

2.3. Nanofibers Fabrication Techniques

Nanofibers have recently become a popular research topic in science and industry. The market size for nanofibers would be USD 477.7 million in 2016, according to "Nanofibers Market Size: Share and Trends Analysis Report" [18], and this number will increase in line with the expansion of industrial activities. Possible structures and application areas of nanofibers are given in Figure 2.2 [19]. When Fiber diameter is decreased to the nanoscale, it gains a high specific surface area, more functionality, and excellent mechanical performance. There are many methods to produce polymeric nanofibers, such as solution blowing, phase separation, drawing template synthesis, self-assembly, electro-spinning, centrifugal spinning, etc. Recently, the techniques of centrifugal spinning, electro-spinning, and solution blowing have become frequently preferred methods. When choosing one of these methods, essential factors include cost, quantity, desired orientation of nanofibers, and expected morphology of nanofiber materials. For instance, electro-spinning or direct coaxial spinning is preferred to produce hollow nanofibers, or phase separation is preferred to create porous nanofibers [20].

2.3.1. Conventional Methods

2.3.1.1. Template synthesis

In template synthesis, a nano-porous membrane is used as a template to obtain nanofibers made of various materials such as conductive polymers, metals, semiconductors, and carbon [21].

In short, under the influence of water pressure, the polymer solution passes through the nanopores of the template and quickly solidifies, and nanofibers are formed (Figure 2.3) [20]. The used template's pore size significantly impacts the fibres' final size, and the resulting nanofibers have low porosity [19].

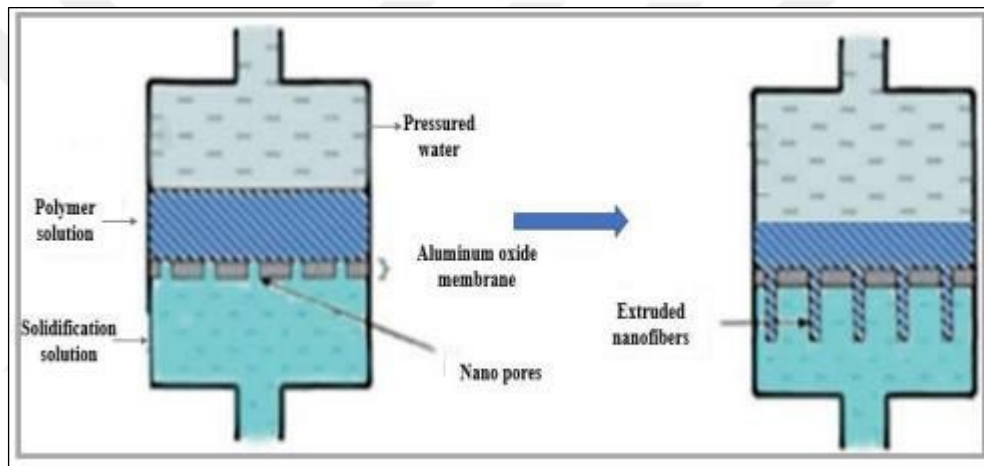


Figure 2.3: Illustration of template synthesis method.

2.3.1.2. Phase separation:

The phase separation process begins with the polymer being dissolved in the proper solvent, and the phase separation stage is then started either thermally or by adding a non-solvent to the prepared solution to create a gel. The solution can separate into two phases because it is thermodynamically unstable under this condition. (Phase rich in polymer 13 and phase poor in polymer). Water is frequently used as a non-solvent, removing the solvent from the gel. As the temperature decreases, the polymer-rich phase solidifies, forming porous nanofibers that range in size from 50 to 500 nm (Figure 2.4) [21-23].

This method is simple and only needs simple equipment, but it is only suitable for a few polymers and gives low yields [21, 22].

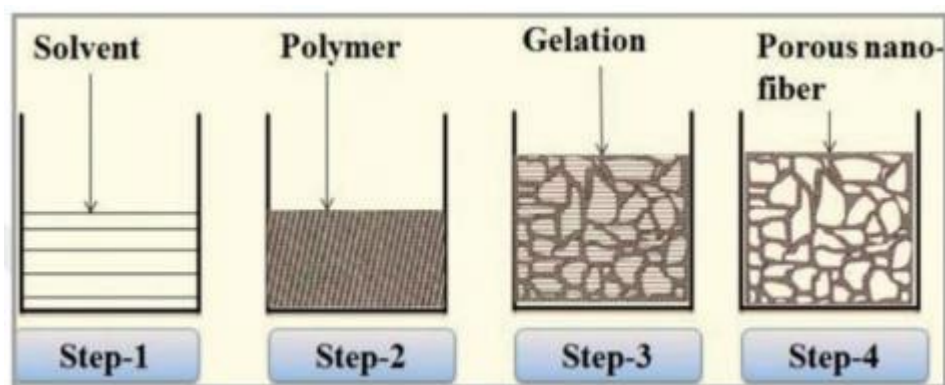


Figure 2.4: Illustration of the phase separation method.

2.3.1.3. Drawing

In this technique, there are three significant steps. In the first step, a drop of the polymer solution is deposited on the substrate substance. In the second step, the micropipette is immersed in polymer droplets. In the last step, contact and by reversing the direction of the micropipette, At a specific rate, the fiber is extracted from the polymer droplet(10-4 m/s) (Figure 2.5) [20, 23].

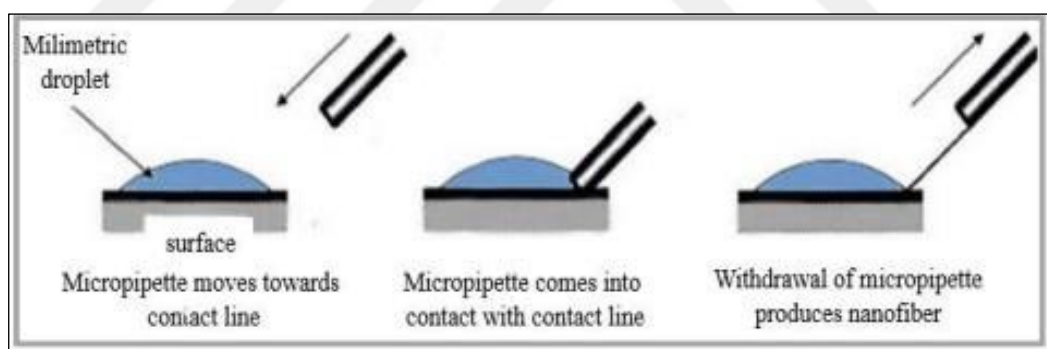


Figure 2.5: Illustration of drawing method.

Uniform nanofibers with a specific size can be obtained by carefully adjusting the drawing speed and solution viscosity. The resulting fibres have a diameter ranging from 2-100 nm to several micrometres and a length ranging from 10 mm to several centimetres [20, 23].

The drawing process does not apply to all polymers (viscoelastic polymers only) and produces a very long single fibre. Although it takes more time, productivity is low. Enables lab-scale production [20, 23].

2.3.2. Modern methods

2.3.2.1. Electro-spinning:

Electro-spinning is a practical and incredibly effective technique for fabricating polymer-based nanofibers and is known as the most established method for producing nanofibers.

Nanofibers (NF) are produced from polymer solutions or melt polymers with electrostatic and Coulombic forces in electro-spinning. The main feature that characterizes this method from others is that the diameters of the produced fibers can be easily adjusted by changing production parameters. Electro-spinning technique is also simple to use, and its cost is reasonable [24].

Figure 2.6 shows the electro-spinning process's main components, including the power supply unit, syringe, drum collector, and high-voltage power supply.

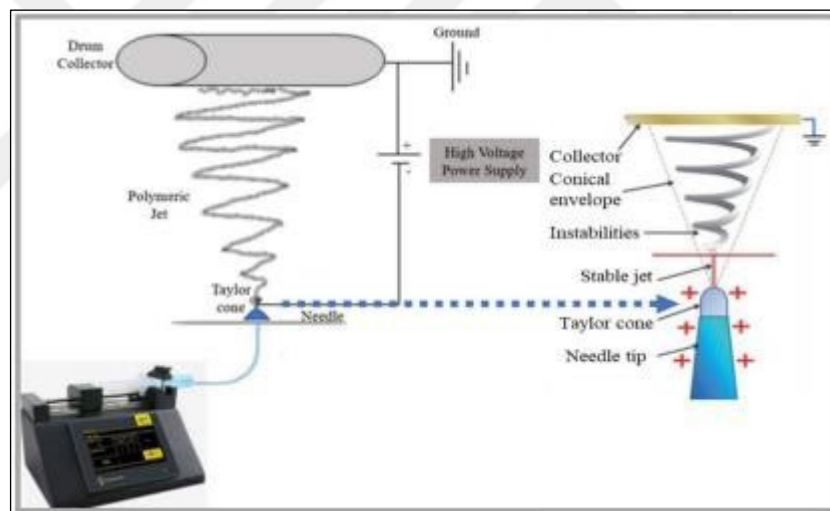


Figure 2.6: Illustration of electro-spinning set-up.

In this process, the polymer is either melted by heat or dissolved in any suitable solvent. An appropriate syringe pump is then pumped to the needle's tip. The hemispherical shape of the droplet starts to change and take on a conical shape, known as a Taylor cone when high voltage electrostatic forces overcome the droplet's surface tension on the needle. First, a stable straight jet is seen near the needle tip when the critical voltage is surpassed. Two or more jets of droplets form when a low-viscosity polymer solution is used because of the long axis.

Surface tension-induced Rayleigh instability. To produce a single jet, a polymer solution with the ideal viscosity should be prepared [25]. Under the influence of electrostatic forces, this jet expands and whips, which causes the solvent to evaporate.

Second, as the stretch increases, the jet enters a phase of unstable bending, and the jet trajectory increases until it reaches the collector. Thus, the size of the fiber becomes tapered as the solvent evaporates and the path of the jet increases. Finally, we obtain solid fibres on the grounded collector whose size varies from nanometre to micrometre [19].

Several parameters influence the final properties of nanofibers in electro-spinning and can be divided into three major categories: process, performance, and environmental. In Table 2.2, their impacts on the morphology of nanofibers are shown. More than 100 different natural and synthetic organic polymers have been used to produce nanofibers with various diameters using this comparatively easy method [19, 26].

In addition to polymers, today's electro-spun nanofibers can be manufactured from ceramics, metals, metal oxides, organic and inorganic composite materials, and metals.

These copolymer-based, blended, or organic filler electro-spun membranes consistently display better mechanical behaviour, barrier properties, and thermal stability [27, 28].

3. POLYVINYLIDENE FLUORIDE (PVDF)

Poly (vinylidene fluoride) (PVDF) has received interest from the material science fields since Kawai discovered the piezoelectricity in stretched and poled PVDF films in 1969 [29] and initially determined that PVDF's g_{32} (piezoelectric voltage constant) and d_{32} coefficients (piezoelectric strain constant) were larger than those of other polymers. The pyroelectricity of PVDF then after that was discovered by Bergmann [30].

Polyvinylidene fluoride (PVDF) is a popular organic ferroelectric material because it has High pyroelectric and piezoelectric properties, excellent mechanical strength even at high temperatures, high dielectric strength, a high melting point, exceptional chemical stability, resistance to hydrolysis and ultraviolet radiation, good corrosion resistance, and extraordinary ignition resistance. Due to these characteristics, this polymer is appropriate for various technical applications, such as sensors, actuators, and non-volatile memory devices [31, 32].

Polyvinylidene fluoride (PVDF) and its copolymer polyvinylidene fluoride-trifluoro ethylene (PVDF-TrFE) are the most widely used polymer matrices in electronic applications due to their superior dielectric strength and comparably higher dielectric constant than other polymer matrices [33].

PVDF is a semi-crystalline polymer with a repeating unit, the $-\text{CH}_2\text{-CF}_2-$ monomer. The high electronegativity of the fluorine and hydrogen atoms in PVDF is what gives it its dipole moment. The orientation of the dipoles is directly controlled by the molecular conformation and the packing of their molecules during the crystallization of PVDF [33-35].

Significantly, the strong dipole in the CF_2 units located along the polymer chain is where PVDF's dielectric and ferroelectric properties originated from [36]. Because of this, PVDF and its copolymers have a comparatively high dielectric permittivity and are exceedingly used as the polymer matrix for organic-inorganic dielectric capacitors.

PVDF possesses unique piezo/pyro/ferroelectrics, low weight, biocompatibility, flexibility, good chemical/thermal, high mechanical, and economic qualities, including excellent creation of non-toxic fibres/films [37].

Semi-crystalline PVDF polymers have a complicated structure with four different crystalline phases: α (or form II), β (form I), γ (form III), and δ (form IV) [29], [38]–[40], and these phases related to various chain conformations TTT (all trans) planar zigzag for the β -phase, TGTG' (trans-gauche-trans-gauche) for the α and δ phases and T3GT3G' for γ phases [41]. Figure (3.1) [42] shows the PVDF phases that are most often utilized for applications and research: α , β and γ . The δ -phase, created by polarizing crystals of the α -phase at a strong electric field (1.25 mV/cm), is a mirror-image of the α -phase with an orthorhombic lattice. α -phase is the most stable, and the β -phase is the best of all due to its superior piezo/pyro/ferroelectric properties [37, 43, 44].

Because of its excellent thermodynamic stability, the non-polar phase is often formed via crystallization from melts, Dimethylformamide, or dimethylacetamide solutions at temperatures over 120 °C [45]. The antiparallel orientation of the dipole components perpendicular to the chain axis eliminates the net dipole moment in-phase PVDF [29]. Despite the internal dipole moments of the α -phase having disappeared, electroforming can still produce the polar analogue in the δ -phase[38]. Hysteresis begins to manifest as the electric field is progressively increased. If the electric field approaches 250 MVm⁽⁻¹⁾, the α -phase paraelectric PVDF becomes a δ -phase ferroelectric.

Due to the alignment of all the dipole chains in one orientation, β -phase PVDF has a very high dipole moment. High spontaneous polarization is produced in a unit cell by this mass formation (TTTT), which is an outstanding property of thermal, piezoelectric, and ferroelectric films [39, 40]. The high electronegativity of fluorine atoms compared to those of hydrogen and carbon atoms leads to the occurrence of strong electrical moments in the monomeric unit of PVDF. Therefore, each chain has a dipole moment perpendicular to the polymer chain. In the polar β -phase conformation, parallel dipoles are formed by the packing of crystals by the polymer chains, producing a non-zero net dipole moment due to its large piezoelectric coefficient, ferroelectric properties, and pyroelectricity, the molecular conformation of the PVDF's β -phase is the essential phase for technological applications.

Consequently, enhancing the β -phase content of the PVDF matrix has always been a crucial objective. Traditionally, the β -phase is obtained by mechanically extending non-polar α -phase materials [41]. However, this method has obvious

disadvantages for electronic applications, which generally require the fabrication of thin films directly on substrates. Another method for producing phase PVDF (e.g., from Dimethylformamide) at temperatures below 70 °C is solvent casting from a suitable solvent. In contrast, low-temperature evaporation of ferroelectric polymers yields films with high porosity and poor electrical mechanical properties [41].

According to a few studies, incorporating nanofillers such as graphene oxide enhanced the electroactive β phase content.[46], BaTiO₃ [47] clay [48] and ferrite nanoparticles [49] in the polymer. However, the ferroelectric hysteresis loop was not observed in most of the reported films, most of which were manufactured by solvent casting and have a thickness greater than 20 m. One possible explanation is that the PVDF nano-composite films produced by this method have substantial porosity, resulting in poor electrical properties, and it is challenging to apply sufficient voltage to such a dense film. There are no reports of PVDF nano-composite thin films with desirable electrical properties at present.

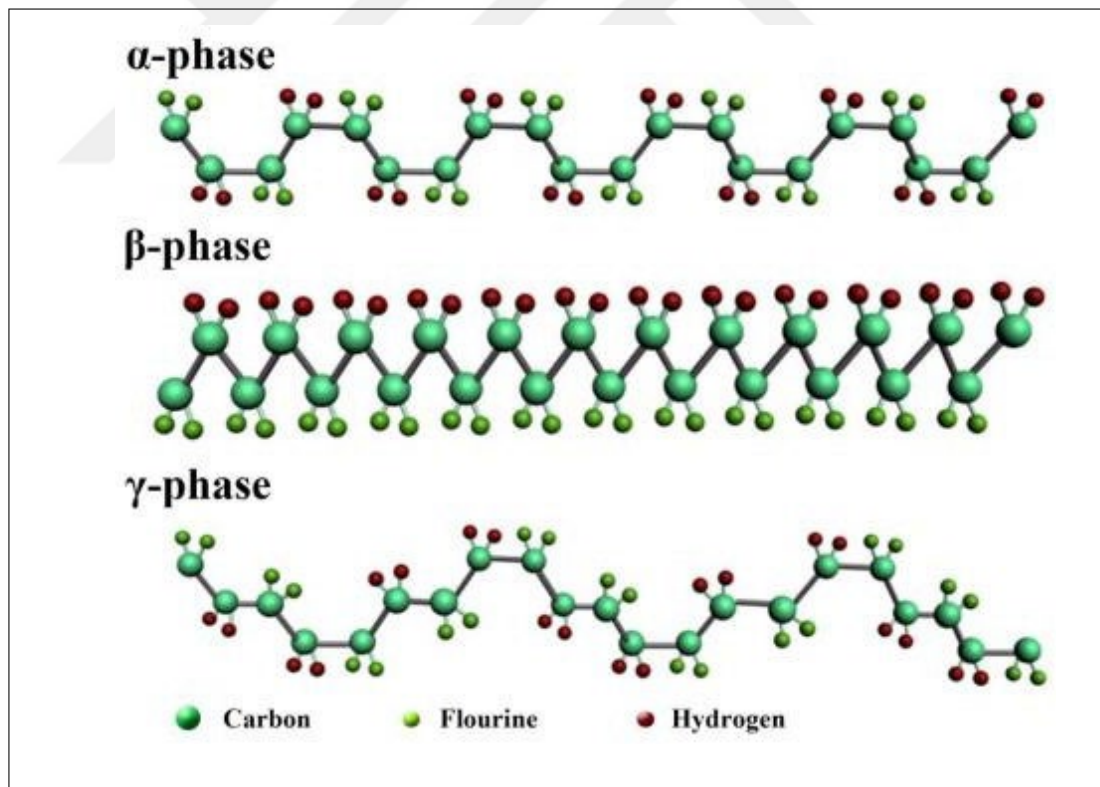


Figure 3.1: Schematic representations of the chain conformation for PVDF's α , β , and γ phases.

4. POLYVINYLIDENE FLUORIDE (PVDF)

TEMPERATURE SENSOR

The rapid development of portable electronic devices [50, 51] has led to substantial study and use of temperature sensors that can provide accurate and straightforward thermal monitoring. Conventional temperature sensors depend on a constant chemical power source, which limits the widespread deployment of these sensors. Moreover, the dependence on an external power source hinders the establishment of sensor networks, especially in challenging or extreme environments. Additionally, the increasing threat of global warming and the global energy crisis has spurred action towards self-powered sensors [18, 52]. Temperature sensors are widely used in a wide range of applications. These applications include environmental monitoring through ambient temperature measurement, temperature regulation in residential and commercial settings, power and temperature management in electronic devices, monitoring of food products with RFID technology, and providing temperature compensation for sensory systems.

Modern electronics frequently employ four primary categories of temperature sensors: thermocouples, resistance temperature detectors (RTDs), thermistors, and integrated circuits (ICs) based on semiconductor technology. Each of these temperature sensor types possesses its unique merits and drawbacks. Consequently, the selection of a sensor depends on the application and its associated requirements. A Polyvinylidene Fluoride (PVDF) temperature sensor is a type of temperature sensor that uses PVDF material as its sensing element. Polyvinylidene fluoride (PVDF) is a thermoplastic polymer with unique properties that make it appropriate for a variety of applications, including temperature sensors. Here are some of the properties of PVDF that make it an excellent choice for temperature sensors:

1-High Sensitivity: Because of the piezoelectric characteristic of PVDF, temperature sensors with high sensitivity can generate an electrical charge in response to mechanical stress or deformation. This property enables PVDF temperature sensors to detect and respond to even slight temperature variations with high accuracy.

2-Chemical Resistance: Polyvinylidene fluoride (PVDF) is well-known for its outstanding chemical resistance. It can withstand interaction with various chemical

compounds, including acids, bases, and organic solvents. This property distinguishes PVDF as a preferred material for circumstances in which sensors or other components may meet corrosive chemicals.

3-Electrical Insulation: PVDF possesses exceptional electrical insulating properties, making it suitable for applications that require electrical isolation.

4-Low Thermal Conductivity: PVDF (Polyvinylidene fluoride) has a poor thermal conductivity, which might be useful in temperature sensing applications when heat transmission from the environment to the sensor is desired.

5-Ease of Processing: PVDF (Polyvinylidene fluoride) is easily processed and may be moulded or extruded into various forms to generate various temperature sensor devices.

6-Cost-Effective: In comparison to other specialized polymers, PVDF is often recognized as a cost-efficient material for temperature-sensing applications [53].

Although PVDF possesses these desired features, the specific performance of a PVDF temperature sensor may vary based on its design, manufacturing method, and any extra coatings or treatments added to it. As a result, when selecting a PVDF temperature sensor for a given application, it is necessary to consider the requirements and specific conditions of that application, which must be examined to ensure sensor appropriateness and performance.

PVDF temperature sensors are widely employed in various industries and applications, such as traffic motion sensors, pressure sensors, sound emission monitoring tools, displays, robots, and artificial muscles, among other applications. PVDF may be used to make temperature sensors in a variety of ways. One way involves using a triboelectric nanogenerator (TENG) as a self-powered temperature sensor with PVDF and polytetrafluoroethylene (PTFE) [54]. In this set-up, the temperature-induced rise in sensor output voltage follows a linear relationship with rising temperatures. Another way is to use a capacitive temperature sensor based on a PVDF capacitor.

Naveed Khan et al. studied a PVDF temperature sensor's temperature-dependent Capacitance (CT) behaviour below the Curie point. Multiple measurements of the capacitor were taken during their studies, which showed good repeatability. They discovered that the PVDF capacitor's Capacitance varies with temperature and has a sensitivity of 16 pF/°C [55]. The oscillator output frequency varies with temperature

in the LC oscillator circuit, which is built using a PVDF capacitor. At $T_0=2^\circ\text{C}$, the PVDF capacitor has a capacitance $C_0=2.3\text{ nF}$. The oscillator's resonant frequency, which was initially close to 3.4 MHz at room temperature, changes from 3.44 MHz to 3.1 MHz when the temperature rises from 25°C to 70°C . Due to the linear connection between capacitance and temperature, PVDF temperature sensors that operate below the Curie point provide accurate readings with excellent measurement accuracy [55].

4.1. PVDF temperature sensor principal work:

PVDF temperature sensors work on the premise that the piezoelectric properties of PVDF change with temperature. When PVDF is exposed to temperature changes, it suffers mechanical deformation, because of which its piezoelectric response changes. This difference in response can be measured and associated with temperature changes.

4.2. PVDF temperature sensor applications:

Environmental monitoring: The flexible PVDF temperature sensor demonstrated its capability to generate various piezoelectric signals in response to varying sound, wind, or humidity levels in everyday surroundings. This sensor holds the potential for monitoring environmental conditions. The sensor must possess a high sensitivity due to the highly faint vibrations generated by sound or wind [56].

Using PVDF, Kequan Xia et al. developed a self-powered temperature sensor based on a triboelectric nanogenerator (TENG). Polytetrafluoroethylene and polyvinylidene fluoride, as well as conductive copper foil, were used to produce triboelectric pairs. The conductive copper foil was used as the conductive electrode. The temperature sensor displays a proportional rise in output voltage as temperatures increase, boasting a temperature detection range between 10 to 90°C . It has a response time of around 0.01 seconds, and 3.5 seconds is a reset time. TENG's prospective uses as a temperature sensor show potential in several applications, such as environmental science, security monitoring, and healthcare diagnostics [54].

4.2.1. PVDF temperature sensor in the medical field:

In the medical field, PVDF-based temperature sensors were developed for microfluidic systems. Integrating the sensor into a system-on-a-chip platform enables rapid monitoring of the local temperature of a biological fluid. This helps reduce errors in evaluating thermal changes in the liquid during analysis. The PVDF thin film is integrated with an infrared source, which stimulates the active element in the microfluidic channel's top part to create the contact temperature sensor [57]. The experimental results for the 25 to 65 °C temperature range demonstrate that the sensor's behaviour at any temperature depends on the thermal (rising phase) and electrical (falling phase) properties of the sensor response. PVDF sensors are thus appropriate for applications requiring the local temperature monitoring of biological samples. Additionally, they are a desirable choice for in situ investigation of biological fluids because of their simple integration into conventional microfluidic devices [57].

4.2.2. PVDF temperature sensor in electronic skin application:

Significant progress has recently been achieved in developing sensor systems for robots. Designing and producing electronic skins, or E-skins," for humanoid robots is one of the most critical focuses in this discipline.

A tactile sensor based on PVDF-TrFE/BaTiO₃ was developed to monitor touch and temperature. The sensor is appropriate for applications like e-skin since it is constructed on a flexible polyamide film. The sensor material is made up of barium titanate (BaTiO₃) nanoparticles and polyvinylidene tetrafluoroethylene fluoride (PVDF-TrFE) [58]. A typical temperature range of everyday life is used to test this sensor. The click state under continuous load serves to define touch sensitivity.

5. FUNDAMENTALS OF DIELECTRIC THEORIES

5.1. Dielectrics and insulating materials

Materials can be divided into three groups based on their capacity to enable charges to pass through them. Conductors, semiconducting materials, and insulators make up these categories. Conductivity, which spans 26 orders of magnitude, is the physical quantity that best characterizes the properties of this material.

Because our technological civilization and daily life activities rely on the safe and user-friendly distribution of electrical energy, the electrical performance of materials is essential. Due to this, conductors and insulators are necessary, whereas semiconductor materials constitute the foundation of numerous electronic devices and the era of informatics.

Recent research has focused on developing electrically functional materials, enhancing electrical performance, and studying the electrical behaviour of nanoscale materials (nanostructured materials, nano-composites, etc.).

Even though dielectric materials refer to a broader class of materials as absolute counterparts, the words dielectric materials (or dielectrics) and insulating materials (or insulators) are employed.

Dielectric materials have low conductivity and an energy band gap greater than 3 eV. Insulators are dielectric materials used in electrical devices to prevent the flow of charges or leakage currents.

When an electric field is applied to a dielectric substance, positive charges are forced in the field's direction, while negative charges are forced to the opposite. Consequently, positive and negative charges are separated in each fundamental volume of the material, while the dielectric remains neutral overall. During this process, electrons are moved from their equilibrium location by distances smaller than the atomic diameter; however, no macroscopic charge migration, as would occur in a conductor, appears to occur [59].

5.1.1. Electric Dipole Moment

The electric dipole moment of a charge distribution determines a vector from the centre of negative charge to the centre of positive charge; the equation gives its magnitude: (4.1).

$$\mu = qr \quad (5.1)$$

Here q is the absolute value of a positive or negative charge, r is the separation between two charges.

When different kinds of dipoles are present in a material, the total dipole moment is given by Eq (4.2). The unit of polarization is (C/m^2) and practically corresponds to the surface charge density σ .

$$M = \sum_i q_i r_i \quad (5.2)$$

Here i refer to the number of different dipoles. A dielectric material's polarization P expresses the total dipole moment per unit volume, as shown by Eq (2.3).

$$P = \frac{M}{V} \quad (5.3)$$

Here V the volume of the sample.

5.1.2. Electric field(E))

The electric field (or intensity of the electric field) E is the force exerted on a unit charge within the field.

$$E = \frac{F}{q} \quad (4.4)$$

The expression for the electric displacement D is.

$$D = \epsilon_0 E + P \quad (4.5)$$

Here ϵ_0 is the permittivity of space ($\epsilon_0 = 8.854 \times 10^{-12} \text{ F/m}$).

5.1.3. Dielectric constant ϵ_r

The dielectric constant can be seen in the expression of the force between two-point charges, e and e' , placed in an unconfined homogeneous dielectric medium and separated by r .

Here force $= e e' / \epsilon_r r^2$.

ϵ_r The dielectric constant is the characteristic constant of the dielectric medium between two charges. The dielectric constant of a material can also be defined as the ratio of the field strengths of the same number of separated charges in space and inside the material[60].

A parallel-plate capacitor with two conducting plates of area A and separated by a distance d explains the dielectric behaviour, as shown in Figure (2.1) [60].

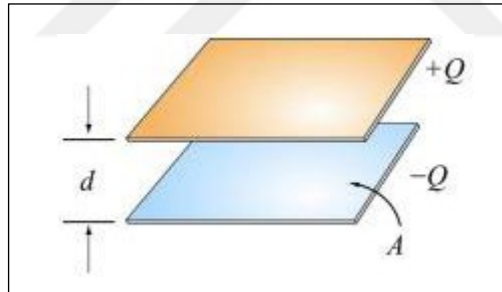


Figure 5.1: A parallel-plate capacitor.

Suppose this capacitor is charged with a charge of $+Q$ on the upper plate and $-Q$ on the lower plate under the potential difference V with a DC source, and the power supply is disconnected. Between the charges accumulated on the armatures of the capacitor, a potential difference of V is created. The potential difference V is directly proportional to the charge Q on the armatures.

$$Q = CV \quad (4.6)$$

C is the proportionality constant called the Capacitance. The charge Q accumulated on the plates is in terms of surface charge density σ_s , and the potential difference V is the electric field.

Where equation 2.1 is rewritten in terms of E,

$$Q = C.(Ed) = \sigma_s A \quad (4.7)$$

can be written as

$$C = \frac{Q}{V} = \frac{\sigma_s A}{Ed} = \epsilon \frac{A}{d} \quad (4.8)$$

ϵ is the dielectric permittivity of the material between the plates and M.K.S. The dielectric permittivity of the space in the unit system is $\epsilon_0 = 8.857 \times 10^{-12} (F/M)$ [60].

The dielectric constant of a material (relative dielectric permeability) is the ratio of the dielectric permittivity of the material to the dielectric permittivity of the cavity and is represented as

$$\epsilon_r = \frac{\epsilon}{\epsilon_0} \quad (5.9)$$

5.2. Classification of dielectric materials

Polar and non-polar dielectrics are the two fundamental categories of dielectrics.

1. Polar dielectrics: Polar molecules of dielectrics exhibit permanent electric dipole moments without an applied electric field because the centres of the positive and negative charge distributions do not coincide. Polar dielectrics contain non-symmetric molecules, with the dipole moment increasing as the difference in electronegativity between the elements constituting the molecule grew.

2. Non-polar dielectrics: Due to the symmetrical distribution of positive and negative charges, the molecules of non-polar dielectrics lack a persistent electric dipole moment. Which causes the foci of their charge distributions to coincide. The arrangement of non-polar molecules in space is symmetrical with a geometrical centre of symmetry.

Due to their spherical-type symmetry, atoms do not exhibit permanent electric dipole moment. However, acquires come polarized under the influence of an applied field and, as a result, acquires an induced dipole moment in the direction of the field. Due to the applied moment when a polar molecule is subjected to an electric field, it tends to align with the direction of the field. Under an applied field, polar molecules and atoms behave as dipoles in the direction of the active (local) electric field figure (4.4) [59].

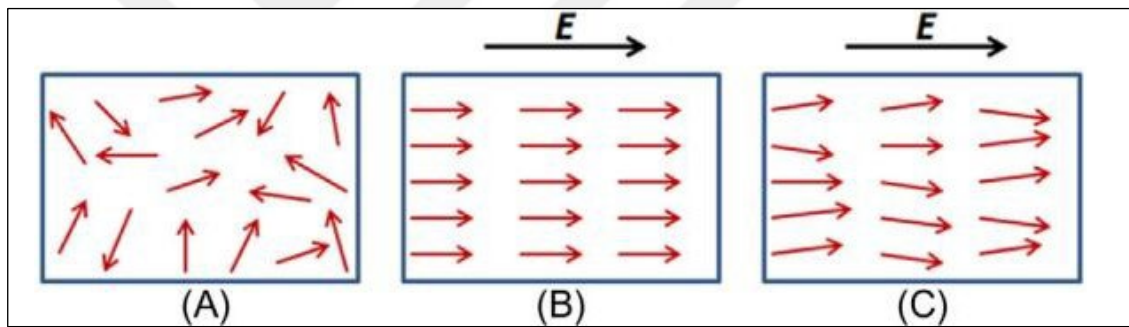


Figure 5.2: A permanent electric dipole's orientation in response to an external electric field. A) In the absence of an electric field, B) under the influence of an electric field with no molecular interactions, and C) under the influence of an electric field with molecular interactions.

5.3. Ferroelectric Materials

Ferroelectric materials are known for their switchable spontaneous polarizations, which respond to outside stimuli such as stress, temperature, electric field, and magnetic field (for multiferroic materials). Ferroelectric materials, called "smart materials," are widely used in sensors, actuators, field effect transistors, and memory devices.

Ferroelectricity is the property of a material with two properties: spontaneous polarisation and the ability to reverse when exposed to external electric fields[61]. First observation of the ferroelectric property in Rochelle salts. The name comes from the analogy with ferromagnetism, which is a magnetic property of a material with a permanent magnetic moment [62, 63]. The prefix Ferro, which means Iron (Fe), was used at the time due to the element's presence in magnetic materials. Although some ferroelectric materials contain Iron, ferroelectricity has nothing to do with Fe.

Dielectric polarisation generally occurs when an external electric field polarizes a material; induced polarization (p) is linearly proportional to the magnitude of the applied external electric field (E).

The ferroelectric materials lose their spontaneous polarization property and turn paraelectric above the critical temperature, or the Curie temperature or transition temperature. In this case, there is nonlinear polarization to an external electric field. Because of this, the electrical permittivity is not constant as a function of the slope of the polarization curve.

In a ferroelectric material, the electric dipoles are coupled to the crystal lattice of the material, so the strength of the dipoles could change by the variation in the lattice, i.e., the strength of the spontaneous polarization.

When a ferroelectric substance is transformed into a capacitor without the aid of an outside field, The surface charge current flow changes because of the spontaneous polarization change. Two stimuli can change a ferroelectric material's structure: mechanical force and temperature [64].

Application of external stress causes the generation of surface charge, known as piezoelectricity, while the change in temperature leads to a change in spontaneous polarization, called pyroelectricity.

There are several attractive interrelationships involving crystal formations between piezoelectricity and pyroelectricity, which lead to an understanding of ferroelectricity. All crystals can be classified into 32 different groups. There are 32-point groups in the seven basic crystal systems. Among the 32-point groups, there are 21 non-centrosymmetric classes, which is a necessary condition for piezoelectricity. Twenty of them are piezoelectric. Among the 20 piezoelectric crystal classes, 10 crystals have pyroelectric properties. Under a specific temperature range, this class of materials is permanently polarized.

General piezoelectric polarization is produced. Under stress, the pyroelectric polarization develops spontaneously and remains as permanent dipoles in the structure. Pyroelectricity is the term used to describe the response since this polarization changes with temperature.

The pyroelectric group includes ferroelectric materials as a subgroup. That exhibits spontaneous polarization. On the other hand, these two polarizations are distinct from one another because an external electric field can reverse ferroelectric polarization. Piezoelectric, pyroelectric, ferroelectric, and general dielectric materials and their relationships to one another are all summarized in figure (4.5) [64].

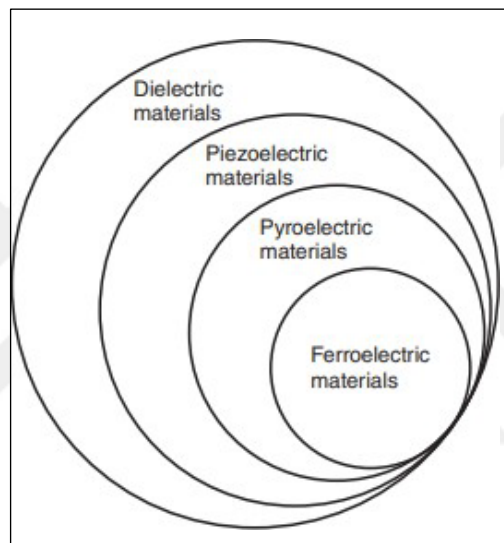


Figure 5.3: Relation between dielectric, pyroelectric, ferroelectric, and piezoelectric materials.

5.3.1. Phase transitions of ferroelectric material

A phase transition is a collective phenomenon where critical behaviour is universal across multiple systems and depends on a small number of parameters.

A phase transition is the change in a material's thermodynamic system from one phase or state to another [65]. During a phase transition of a particular medium, a specific property of the medium changes, often discontinuously.

The phase transition involves a change in symmetry and can be categorized into first and second-order phase transitions depending on whether the transition is discontinuous or continuous. Paul Ehrenfest categorized phase transitions according to how Gibbs thermodynamic free energy changes because of other thermodynamic

factors. Phase transitions were identified using this system by the Gibbs free energy's lowest derivative, discontinuous at the transition.

5.3.1.1. Phase transitions of the first order

First-order phase transitions show a discontinuity about the thermodynamic variable in the first derivative of the Gibbs free energy [65]. At the first-order phase transition, the crystal's polarization, entropy, and volume change discontinuously at the transition point. Energy appears as latent heat at the phase transition to the first order in a temperature range within an infinitely narrow range [59, 66].

5.3.1.2. Phase transitions of the second order

Phase transitions of the second order are continuous in a thermodynamic system's Gibbs free energy's first derivative. Variable but shows a discontinuity in the second derivative [65]. Also, volume, entropy and polarization change continuously, while specific heat changes discontinuously.

When the second stage is in transition, there is an absence of latent heat release. However, the coefficient of expansion displays atypical behaviour within a restricted temperature range [59, 66].

These two types of phase transition in ferroelectric materials are named according to the way the demand parameter (polarization) fig (4.6) [59] alters during the transition. In the Curie temperature range (T_c), the bulk polarization undergoes a sudden decrease and ultimately disappears as the temperature increases, as in figure (4.7) [59]. The observed phenomenon can be classified as a phase transition, like the behaviour exhibited by a ferromagnetic substance or a solid material when its temperature surpasses the range of Curie's temperature.

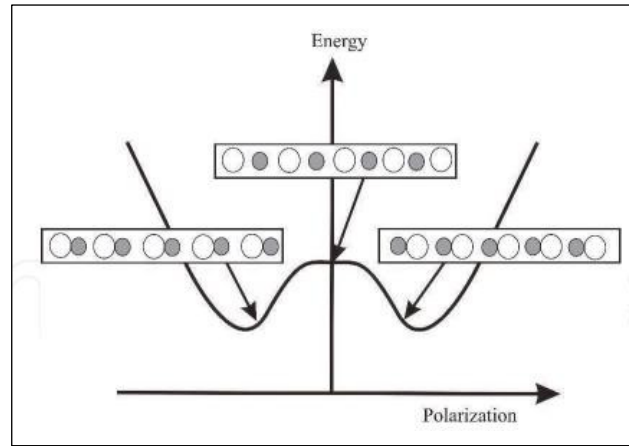


Figure 5.4: Schematic of polarization dependence of potential energy.

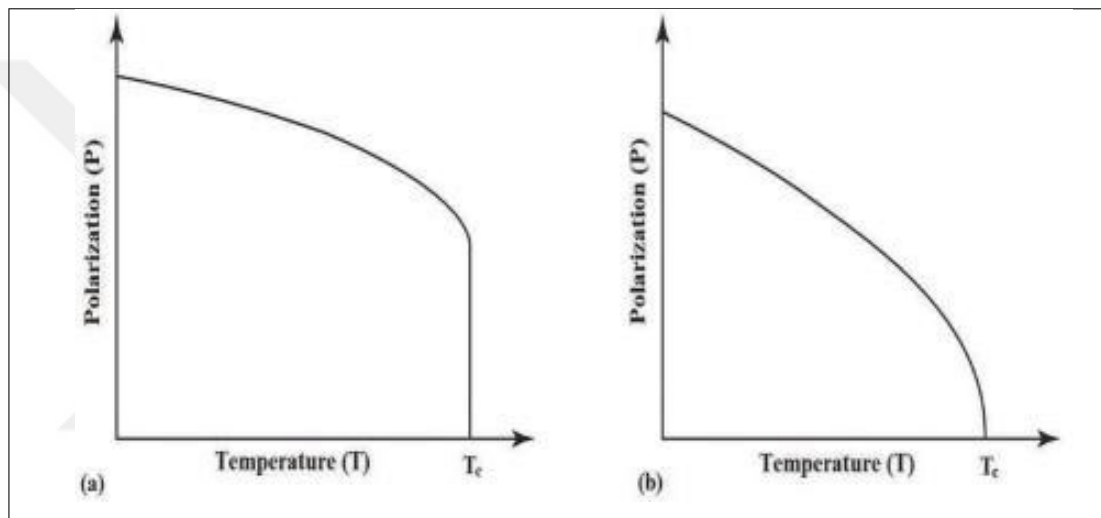


Figure 5.5: Temperature dependence of spontaneous polarization: (a) first-order phase transition, (b) second-order phase transition.

As seen in Figure 4.7 (a), up until the Curie temperature, the polarization is constantly changing in a first-order transition, beyond which there is a break in the continuity. Figure 4.7 (b) shows the absence of the order parameter's first derivative at the Curie temperature in the second-order transition, where the temperature is a constant function of the order parameter itself [59].

5.3.2. Spontaneous polarization

The term "spontaneous polarization" (P_s) describes polarization occurring within a dielectric under the control of internal processes and independent of external influences.

In general, the ferroelectric material crystal is made up of sections with known domains of homogenous polarization. The polarization is in the same direction in each region, whereas polarization in neighbouring areas is in opposite directions. According to that, the polarization value equals zero when no electric field is applied ($E=0$).

Polarization in a nonlinear configuration varies with the electric field (E). When an electric field is applied, this nonlinear relationship is represented by a closed curve known as the hysteresis loop in polarization, as shown in Figure(4.8)[59].

Without an electric field ($E=0$), a single domain specimen's spontaneous polarization (P_s) can be either positive or negative. Induced polarizations such as electronic, ionic, and dipolar polarizations cause the intensity of the applied electric field to gradually increase in the direction of spontaneous polarization (P_s), which leads to polarization increasing (P).

The increase of an electric field causes the growth of the number of domains rotating in the electric field direction(E) until the polarization reaches a maximal level known as the saturation level. At this moment, the entire sample represents a single domain.

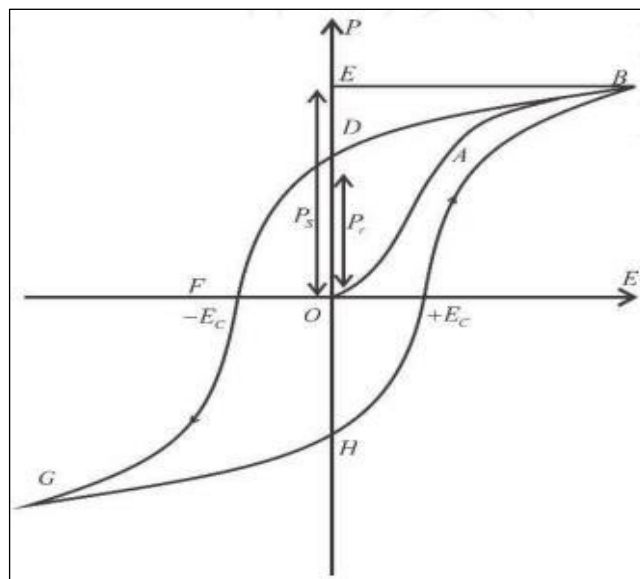


Figure 5.6: Hysteresis loop of ferroelectric material. (P-E)

6. MATERIALS AND METHOD

6.1. Fabrication of Materials

This section includes the study's materials and provides the reasoning behind their choice. Specifically, PVDF was chosen as the polymer material and converted into nanofibers to create a temperature sensor.

The Polyethylene Terephthalate (PET) film used in the study was supplied from Nanjing Crow Lu Ning Pharmaceutical Technology Co., Ltd. and utilized in its original state. Acetone was purchased from Shanghai Ling Feng Chemical Reagent Co., Ltd. China National Medicines Co., Ltd. produced N, N dimethylformamide (DMF), the chemical used in growth. PVDF (FR904), commonly known as polyvinylidene fluoride, was bought from Shanghai 3F New Materials Co., Ltd.

6.2. PVDF NFs and PVDF-Ferrite Nanofiller NFs Preparation

Electro-spinning was used to create pure PVDF NFs and PVDF mixed with ferrite nanofiller NFs-based films. This method allows for the creation of rough surfaces and huge surface areas and is scalable, inexpensive, and straightforward. Consequently, greater charge densities are achievable. The nanofibers' thicknesses are found to be precisely relative to the amount of time electro-spinning at 300 rpm.

In a volume ratio 3:2, a mixed viscous solution consisting of ferrite nanoparticles in mixed N, N Dimethylformamide (DMF), and acetone was made and thoroughly stirred. Next, ten weight per cent of PVDF was gradually added to the solution.

A high-speed stirring procedure lasting one hour at 1000 rpm created a homogenous PVDF- ferrite nanofiller solution [67]. According to Fig. 1, electro-spinning at a voltage of 12 kV was used to create PVDF NFs and PVDF- ferrite nanofiller NFs. 1 ml/h was maintained as the pump rate., and the blunt needle's inner diameter was around 0.8 mm.

The nanofibers were collected using a rotating drum covered with aluminium foil, where they became electrostatically attracted to one another. It rotated at 300 revolutions per minute. The needle was 12 cm away from the drum in motion. An

ambient temperature of $25\pm 3^{\circ}\text{C}$ and a relative humidity of $45\pm 2\%$ were maintained for the electro-spinning process.

6.3. Temperature-dependent Capacitance Measurement Setup

Firstly, the lab temperature is fixed at 23°C before starting experiments. The power supply instrument (SUNLINE 853D) is the voltage source, and LCR (Agilent 4287A) is used to measure the frequency-dependent Capacitance. The PT100 resistor sensor was used with an LS335 Temperature controller (Lake Shore) to measure the temperature of the sample.

The PVDF-ferrite nanofiller nano-composite is placed between two conductive plates, and then a current range between 120-340 mA is applied to heat the sample. The temperature increases up to 60°C as the current increases. The capacitance measurements were performed in the 10-240 MHz frequency range. Data acquisition and calibration procedure software was designed using the LabVIEW environment.

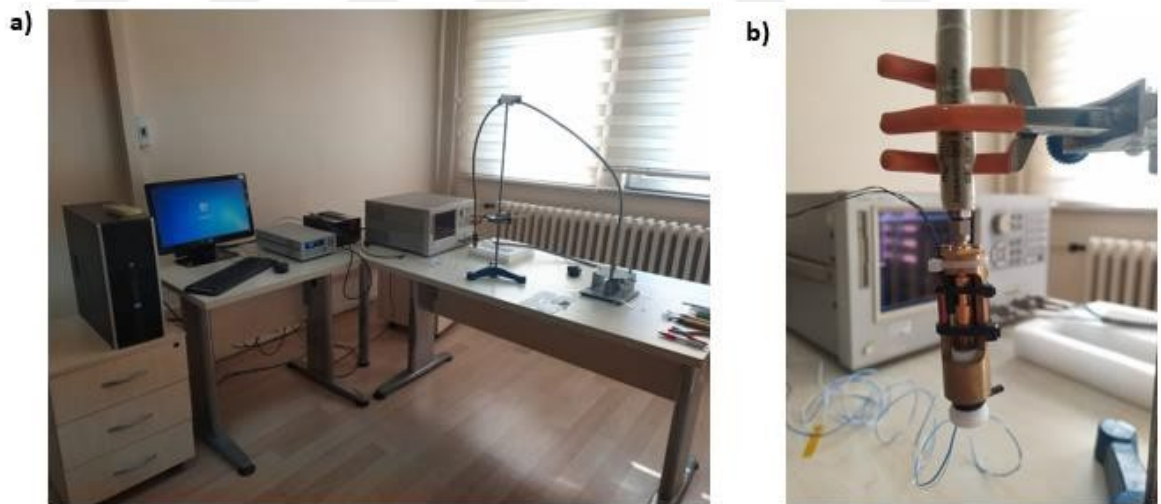


Figure 6.1: Photo of temperature-dependent capacitance measurement set-up (a) general view, (b) in-house designed capacitance measurement probe.

7. RESULTS AND DISCUSSION

7.1. Structural properties

Figure (7.1) shows the SEM surface morphology of PVDF- ferrite nanofiller nanofibers grown for four different durations: 2, 2.5, 3.5, and 4 hours. The presence of ferrite nanofiller in PVDF- ferrite nanofiller NFs resulted in the formation of beads and agglomeration, which decreased as growth time increased, reaching their minimum at the 4-hour growth mark. In the case of PVDF- ferrite nanofiller NFs grown for 2, 2.5, 3.5, and 4 hours, the even distribution of ferrite nanofiller within the NFs is clearly observable.

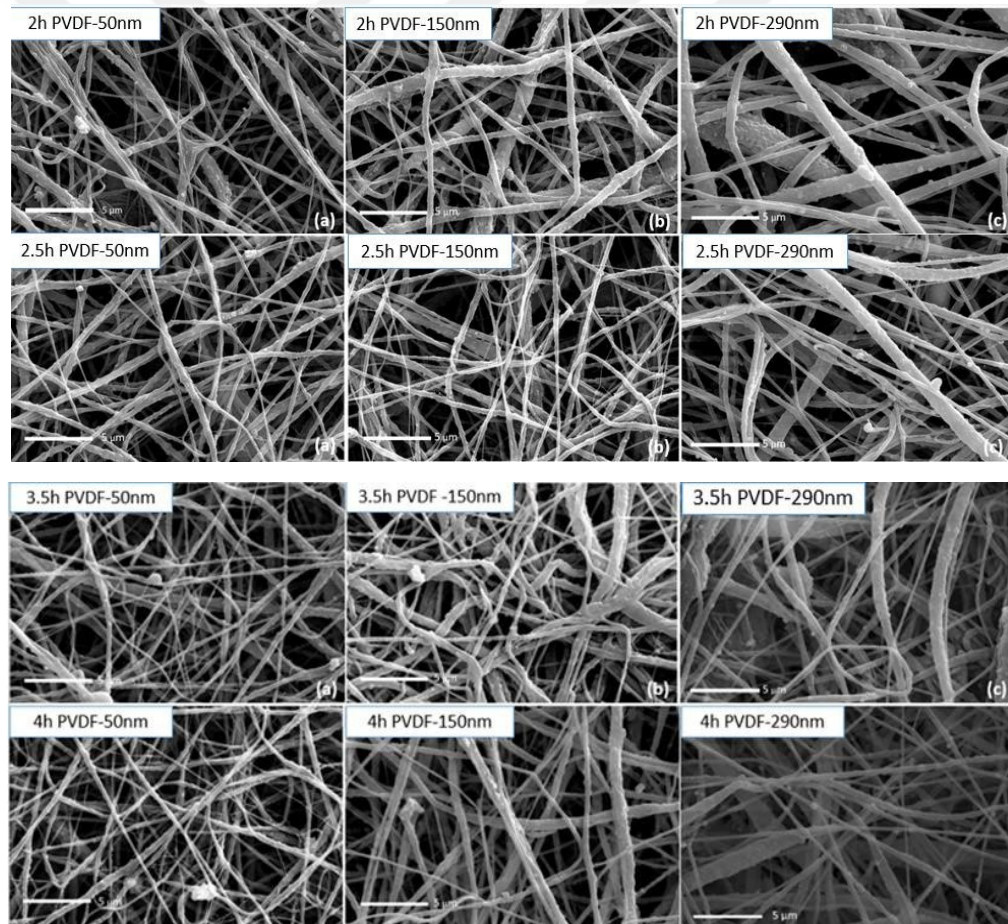


Figure 7.1: PVDF- ferrite nanofiller NFs surface morphology. PVDF with ferrite nanofiller made with various growth times is seen using scanning electron microscopy (SEM).

PVDF nanofiber diameter increases because of the addition of ferrite nano-fillers, their localization inside NFs, or a rise in the viscosity and density of materials around the localized ferrite nano-fillers. Compared to the other PVDF-ferrite nanofiller NFs, the 4 h-grown sample had the biggest NF diameter, denser beads, the most agglomeration, and a heterogeneous distribution of the ferrite nanofiller. These characteristics make surface aggregation more apparent.

Energy-dispersive spectroscopy (EDS) was performed for 4 h-grown samples to investigate the composition of ferrite nanofillers and their function in the NFs. Fig (7.2) for 4 h-grown PVDF- ferrite nanofiller nanofibers, the EDS results show that there are mainly C, O, F and Fe atoms.

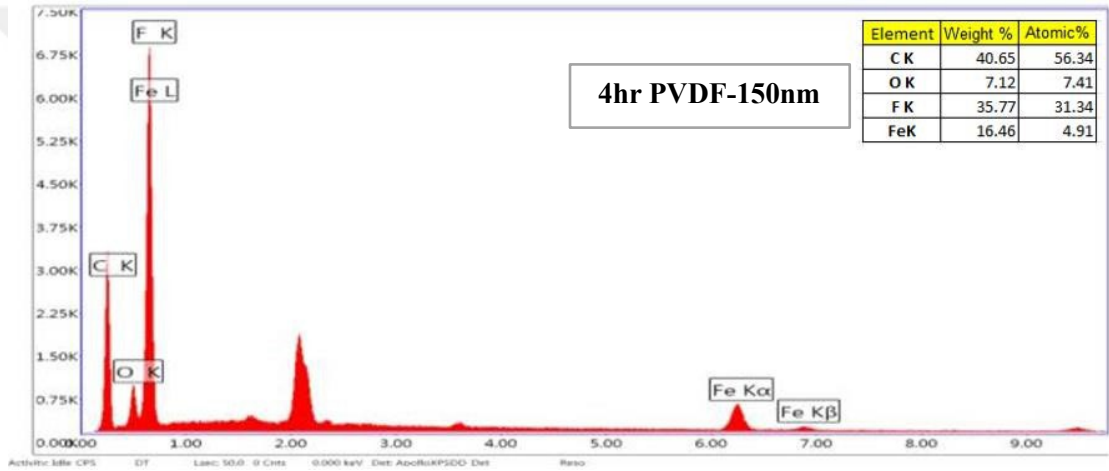


Figure 7.2: EDS spectrum of the PVDF- ferrite nanofiller 4 hours grown NFs.

As depicted in Fig (7.2), in addition to F K, Fe L is present in 4-hour-grown PVDF-ferrite nanofibers, and the combined total fit comprises two Lorentzian components. Furthermore, there is a distinct Fe K α signal in PVDF- ferrite nanofiller nanofibers, indicating the presence of Fe in 4-hour-grown PVDF- ferrite nanofiller nanofibers.

From Figure (7.2), the C, O, and F peaks are bonded to polyvinylidene fluoride (PVDF) polymer. On the other hand, their peaks of Irons bonded to ferrite nanofiller. According to these results, the polyvinylidene fluoride (PVDF) and ferrite nanofiller (FNPs) composite were fabricated successfully.

The composition of ferrite nanofiller for the other samples is included in the table (7.1).

Table 7.1: Composition of PVDF-ferrite nanofiller NFs obtained by energy-dispersive spectroscopy (EDS).

FNPs	Nanofibers (growth time)	Weight				Atomic			
		C	O	F	Fe	C	O	F	Fe
50 nm	2	46.25	5	43.02	5.72	58.97	4.79	34.68	1.57
	2.5	43.95	4.38	42.92	8.75	57.64	4.31	35.58	2.47
	3.5	44.31	4.27	42.24	9.17	58.15	4.21	35.05	2.59
	4	39.36	7.94	35.73	16.97	55.01	8.33	31.56	5.1
150 nm	2	41.27	6.48	38.2	14.05	56.29	6.64	32.95	4.12
	2.5	43.31	6.36	34.37	15.97	59.13	6.52	29.66	4.69
	3.5	40.42	6.74	33.82	19.02	56.97	7.13	30.14	5.77
	4	40.65	7.12	35.77	16.46	56.34	7.41	31.34	4.91
290 nm	2	43.77	4.64	42.65	8.94	57.48	4.58	35.41	2.53
	2.5	42.96	5.22	43.9	7.92	56.27	5.13	36.36	2.23
	3.5	43.45	4.75	44.35	7.45	56.68	4.65	36.58	2.09
	4	43.35	4.85	45.82	5.98	56.12	4.71	37.5	1.66

The crystalline phases of PVDF-FNPs NFs were determined by XRD measurements, as shown in Fig. 7.3 respectively. The PVDF-FNPs show three noticeable peaks at 2θ diffraction angles 21° , 31° , 36° and 44° corresponding to (0 0 1), (2 2 0), (3 1 1) and (1 1 0), which are due to iron oxide, and Iron that are expected to be in the ferrite nanofillers used for the growth. Among all the PVDF-FNPs NFs, the 3.5 h- 50 nm grown sample has clearly. There are much larger peak intensities for all the peaks, particularly those due to the PVDF β phase.

The findings indicate that optimal crystallinity in PVDF-FNPs was achieved when utilizing ferrite nano-fillers with a growth duration of 3.5 hours and a size of 50 nm. These nano-fillers demonstrated superior crystalline properties and were effectively integrated into PVDF, contributing to enhancing its β phase.

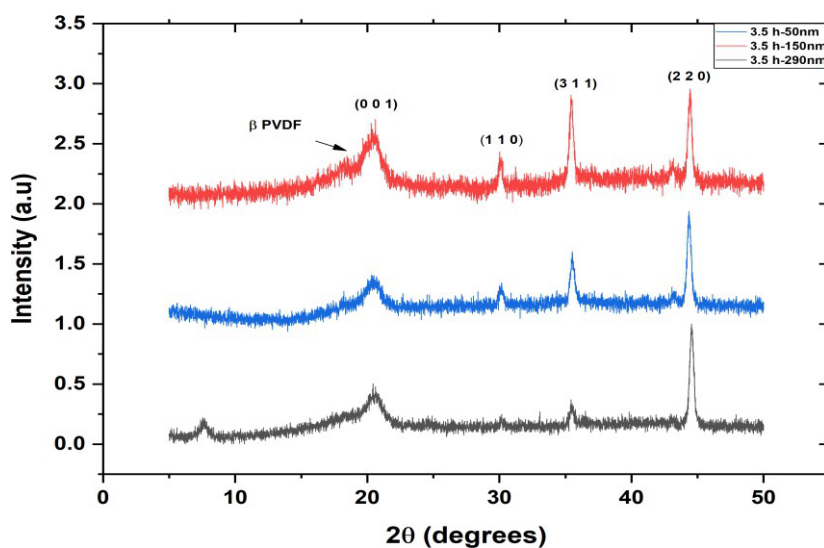


Figure 7.3: XRD characterization PVDF-PI NFs. XRD analysis revealed the presence of ferrite (FNPs) nano-fillers in PVDF, with several peaks. The XRD patterns of PVDF-PI nanofibers grown for 3.5 hours with 50nm ferrite nanofiller demonstrated a distinct improvement in the PVDF β phase at 21°.

7.2. Dielectric properties of PVDF-Ferrite Nanofiller NFs

The Capacitance of PVDF- ferrite nanofiller was studied in the frequency range of 10-240 MHz and temperature range of 23-60 °C.

7.2.1. Temperature effect on Capacitance of PVDF(NFs)- ferrite nanofiller at a constant frequency

To study the effect of temperature on the PVDF-Ferrite Nanofiller NFs capacitance performed at applied frequency 50 MHz and temperature in the range of 23-60°C. Figure (7.3) shows temperature dependence on the Capacitance of PVDF-ferrite nanofiller NFs.

The Capacitance of PVDF (NFs)-ferrite nanofiller sensors increases with increasing temperature. Figure 7.3 shows the linear capacitance increase with temperature for all NPs diameters of ferrite particles with PVDF NFs. It is also seen that the increase of NPs' diameter decreases the temperature response of the PVDF-Ferrite Nanofiller NFs.

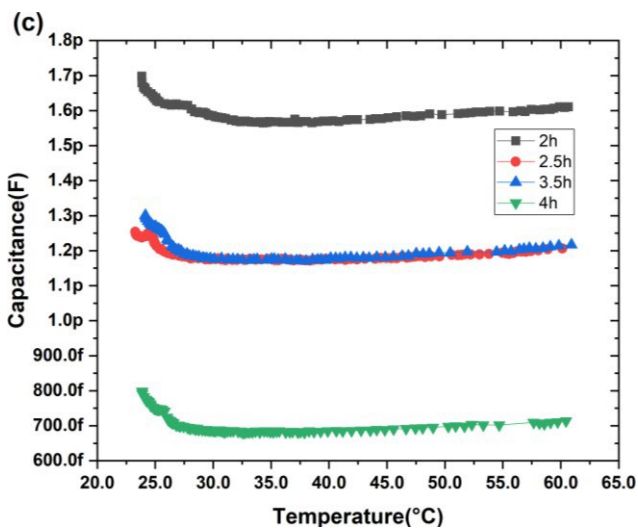
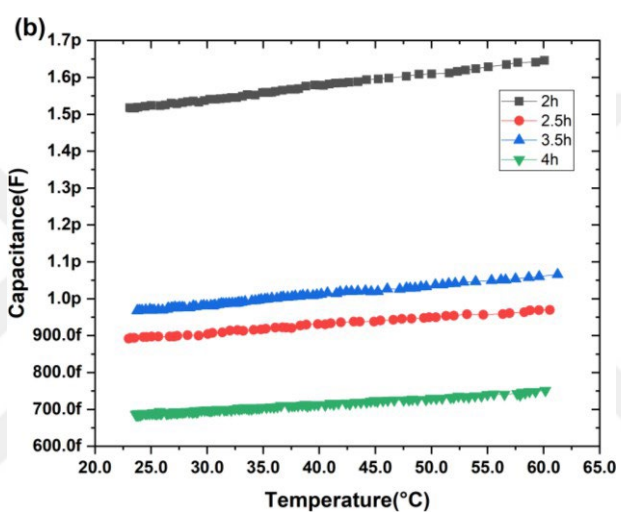
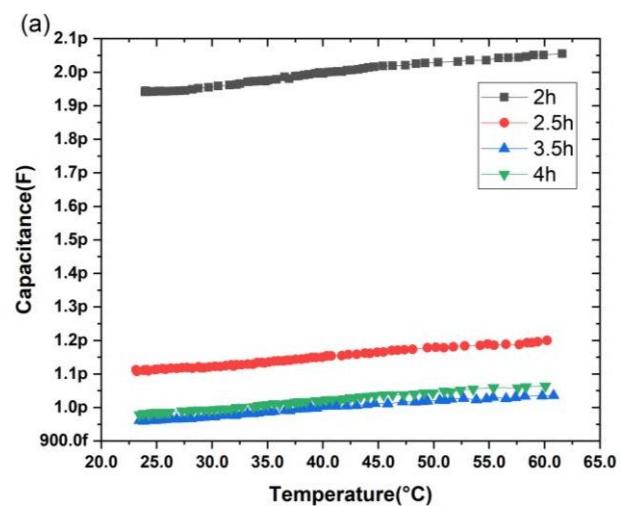


Figure 7.3: Temperature dependence of Capacitance at a fixed frequency (50 MHZ) of PVDF (NFs)- ferrite nanofiller prepared with different growth times of NFs. (a) 50nm in diameter NPs, (b)150nm in diameter NPs, (c) 290nm in diameter NPs.

As the temperature increases, the Capacitance of the PVDF-ferrite nanofiller increases, especially in the case of the nanofibers grown for 2 hours. This phenomenon aligns with the typical characteristics of piezoelectric materials. The elevation in temperature induces greater molecular vibrations within the PVDF nanofibers, resulting in enhanced charge separation and, consequently, higher Capacitance.

PVDF-ferrite nanofiller grown for 2 hours showed a more substantial increase in Capacitance than those grown for longer durations (2.5, 3.4, and 4 hours). This might be due to the specific properties of the nanofibers produced during the 2-hour electro-spinning process. It is possible that the shorter electro-spinning time resulted in nanofibers with different structures or surface properties that respond more sensitively to temperature changes. Results indicate that PVDF nanofibers have a temperature-dependent capacitance, and the electro-spinning time plays a role in the sensitivity to temperature changes. The nanofibers created in the 2-hour electro-spinning process appear to be particularly responsive to temperature fluctuations, leading to a more significant increase in Capacitance as the temperature rises. Further investigation into these nanofibers' specific structure and properties may be needed to understand this behaviour in more detail.

7.2.2. Frequency effect on Capacitance of PVDF-Ferrite Nanofiller NFs

Frequency has an essential influence on capacitors' behaviour; this phenomenon is called capacitive reactance. Capacitive reactance (X_c) measures a capacitor's resistance to alternating current flow. It depends on the frequency of the AC signal and the Capacitance of the capacitor. Capacitance is $C = 1/(2\pi f X_c)$, where C is the Capacitance in farads (F), X_c is the capacitive reactance (Ω), and f is the frequency (Hz). As can be seen from the formula, C is inversely proportional to the frequency. This means that as the frequency of the AC signal increases, the Capacitance decreases.

Figure 7.4. shows the Capacitance of PVDF(NFs)-Ferrite Nanofiller at a frequency range of 10-240 MHz and a fixed temperature of 25°C, the maximum Capacitance of PVDF(NFs)-50nm at 2 h growth time is 1.85 Pf, and the capacitance decrease with frequency increase the minimum Capacitance is 650 fF when the frequency 240 MHz. The frequency response of the measured samples shows ceramic

dielectric materials' typical relaxation behaviours. It is also clearly seen that the relaxation frequencies are in the regime of sub-Mhz frequencies.

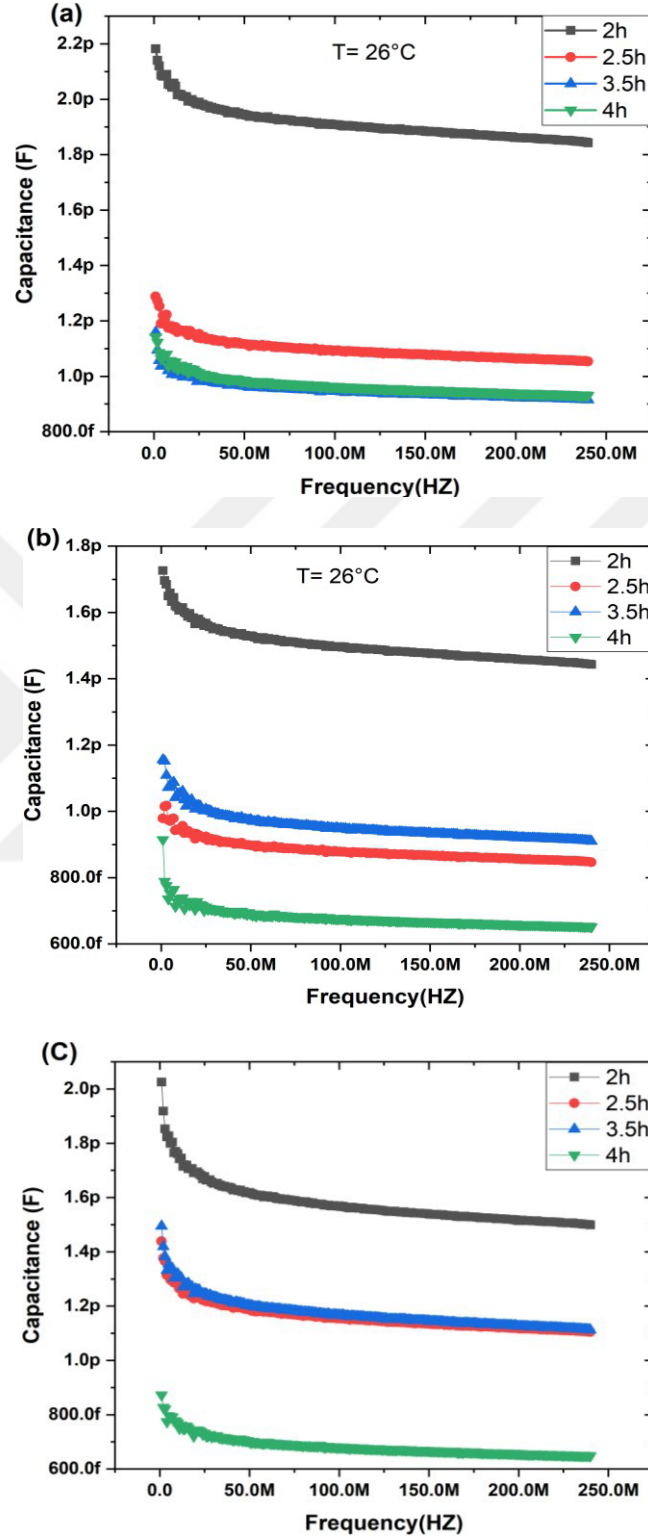


Figure 7.4: Frequency dependence of Capacitance of PVDF (NFs)- ferrite nanofiller at temperature ($T = 25^\circ\text{C}$) (a) PVDF(NFs)-50nm, (b) PVDF(NFs)-150nm, and (c) PVDF(NPs)- 290nm.

Figure 7.5. shows the sensitivity ($\Delta C / \Delta T$) of PVDF (NFs)- ferrite nanofiller, the sensitivity of PVDF-ferrite nanofiller composite decrease as the frequency increase. Figure 7.5. (a) show the maximum value of ($\Delta C / \Delta T$) of PVDF with 50nm ferrite nanofiller value of 1.75 fF, Fig (b) the value of ($\Delta C / \Delta T$) PVDF(NFs)-150nm is 2fF when the electro-spinning time is 2hour, Fig (c) the maximum value of ($\Delta C / \Delta T$) of PVDF(NFs)-290nm is 0.8fF at growth time 3.5h, the value of ($\Delta C / \Delta T$) at growth time 2h decrease to 0.65Ff.

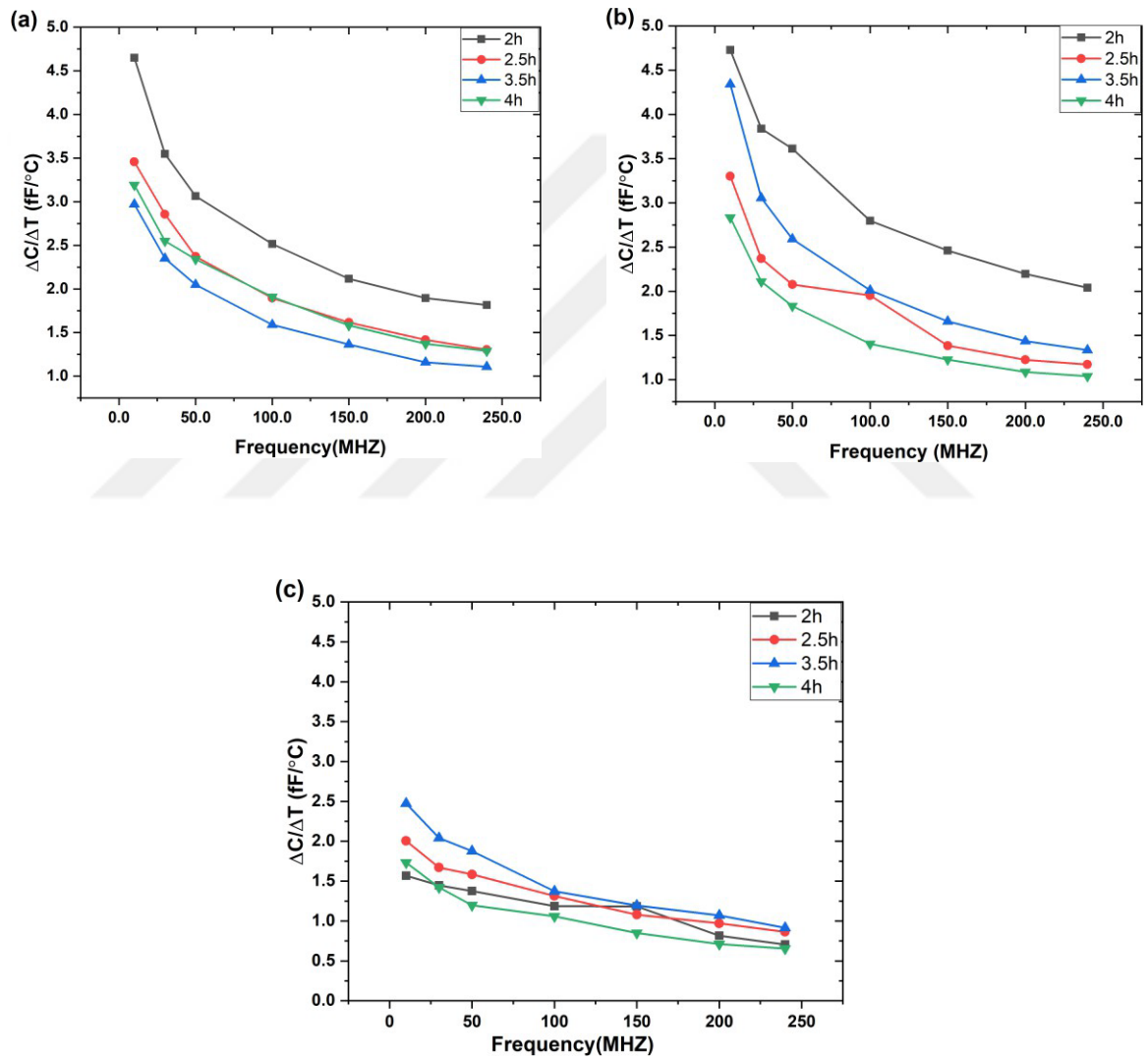


Figure 7.5: Temperature variation of capacitance ($\Delta C / \Delta T$) of PVDF - ferrite nanofiller (a) PVDF (NFs)-50nm(b) PVDF(NFs) -150nm, (c) PVDFNPs)- 290nm.

8. CONCLUSION

The rapid progress in portable electronic devices has led to much research and application of temperature sensors that can provide accurate and straightforward thermal monitoring.

Recently, PVDF nanofibers filled with nanoparticle fillers have demonstrated significant advancements in sensor technology. Further research and development in this field holds great promise for creating susceptible, selective, and reliable sensors for various applications, ranging from healthcare and environmental monitoring to industrial processes and beyond.

Using the electro-spinning technique, Ferrite nano-fillers were integrated into PVDF nanofibers (NFs) to create PVDF-FNPs with varying growth times. These PVDF-FNPs were subsequently employed in the fabrication of temperature sensors.

Temperature sensors employing PVDF-FNP capacitors and operating below the Curie temperature can offer exceptional measurement precision thanks to their linear capacitance-temperature relationship. Their inherent linearity enables these sensors to deliver impressive accuracy while reducing the frequent calibrations required by alternative sensor types.

Our study shows that PVDF NFs with ferrite nanofillers can be capacitive temperature sensors, especially with a significant increase in the temperature sensitivity of these materials at low frequencies.

REFERENCES

- [1] O. Kanoun, A. Bouhamed, R. Ramalingame, J. R. Bautista-Quijano, D. Rajendran, and A. Al-Hamry, "Flexible and Stretchable Strain and Pressure Sensors," *Sensors*, vol. 21, p. 341, 2021.
- [2] M. A. U. Khalid and S. H. Chang, "Flexible strain sensors for wearable applications fabricated using novel functional nano-composites: A review," *Compos. Struct.*, vol. 284, no. December 2021, p. 115214, 2022.
- [3] M. Amjadi, K. U. Kyung, I. Park, and M. Sitti, "Stretchable, Skin-Mountable, and Wearable Strain Sensors and Their Potential Applications: A Review," *Adv. Funct. Mater.*, vol. 26, no. 11, pp. 1678–1698, 2016.
- [4] Y. Zang, F. Zhang, C. A. Di, and D. Zhu, "Advances of flexible pressure sensors toward artificial intelligence and health care applications," *Mater. Horizons*, vol. 2, no. 2, pp. 140–156, 2015.
- [5] A. Valipouri, "Production Scale Up of Nanofibers : A Review," *J. Text. Polym.*, vol. 5, no. 1, pp. 8–16, 2017.
- [6] H. Qiao and Q. Wei, *Functional nanofibers in lithium-ion batteries*, no. Ii. Woodhead Publishing Limited, 2012.
- [7] M. M. Bubakir, H. Li, A. Barhoum, and W. Yang, *Advances in Melt Electro-spinning Technique*, no. April 2018. 2019.
- [8] O. Jirsák and T. A. Dao, "Production , Properties and End-Uses of," pp. 1–5, 2007.
- [9] E. Ghafari, X. Jiang, and N. Lu, "Surface morphology and beta-phase formation of single polyvinylidene fluoride (PVDF) composite nanofibers," *Adv. Compos. Hybrid Mater.*, vol. 1, no. 2, pp. 332–340, 2018.
- [10] N. Bhattarai, Z. Li, D. Edmondson, and M. Zhang, "Alginate-based nanofibrous scaffolds: Structural, mechanical, and biological properties," *Adv. Mater.*, vol. 18, no. 11, pp. 1463–1467, 2006.
- [11] S. G. Kumbar, R. James, S. P. Nukavarapu, and C. T. Laurencin, "Electro-spun nanofiber scaffolds: Engineering soft tissues," *Biomed. Mater.*, vol. 3, no. 3, 2008.
- [12] S. Homaeigohar and M. Elbahri, "Nano-composite electro-spun nanofiber

- membranes for environmental remediation,” *Materials (Basel)*., vol. 7, no. 2, pp. 1017–1045, 2014.
- [13] X. Wang and B. Li, “Electro-spun Nanofibrous Sorbents and Membranes for Carbon Dioxide Capture,” pp. 249–263, 2014.
- [14] B. P. Sahoo and D. K. Tripathy, “Properties and applications of polymer nano-composites: Clay and carbon based polymer nano-composites,” *Prop. Appl. Polym. Nano-composites Clay Carbon Based Polym. Nanocomposites*, pp. 1–222, 2017.
- [15] K. Yoon, B. S. Hsiao, and B. Chu, “Functional nanofibers for environmental applications,” *J. Mater. Chem.*, vol. 18, no. 44, pp. 5326–5334, 2008, doi: 10.1039/b804128h.
- [16] S. Dadvar, H. Tavanai, and M. Morshed, “UV-protection properties of electro-spun polyacrylonitrile nanofibrous mats embedded with MgO and Al₂O₃ nanoparticles,” *J. Nanoparticle Res.*, vol. 13, no. 10, pp. 5163–5169, 2011.
- [17] S. Sundarrajan and S. Ramakrishna, “Fabrication of nano-composite membranes from nanofibers and nanoparticles for protection against chemical warfare stimulants,” *J. Mater. Sci.*, vol. 42, no. 20, pp. 8400–8407, 2007.
- [18] *Handbook of Nanofibers*. Springer International Publishing, 2019.
- [19] X. Gao *et al.*, “Morphology optimizing of polyvinylidene fluoride (PVDF) nanofiber separator for safe lithium-ion battery,” *J. Appl. Polym. Sci.*, vol. 139, no. 20, pp. 1–10, 2022, doi: 10.1002/app.52154.
- [20] I. Alghoraibi and S. Alomari, *Handbook of Nanofibers*, no. February. 2020.
- [21] S. K. Nune, K. S. Rama, V. R. Dirisala, and M. Y. Chavali, *Electro-spinning of collagen nanofiber scaffolds for tissue repair and regeneration*. Elsevier Inc., 2017.
- [22] A. A. Kulkarni and P. S. Rao, *Synthesis of polymeric nanomaterials for biomedical applications*. Woodhead Publishing Limited, 2013.
- [23] T. Garg, G. Rath, and A. K. Goyal, “Biomaterials-based nanofiber scaffold: Targeted and controlled carrier for cell and drug delivery,” *J. Drug Target.*, vol. 23, no. 3, pp. 202–221, 2015.
- [24] Nç. Bezir, A. Evcin, A. Oktay, and A. kelimeler, “Seryum Katkılı TiO₂ Nanofiberlerin Üretim ve Karakterizasyonu Fabrication and Characterization of Ce Doped TiO₂ Nanofiber By Electrospinning Method,” *AKU J. Sci. Eng.*, vol.

- 5748, pp. 311–313, 2014, [Online]. Available: <http://upload.wikimedia.com.org>
- [25] N. D. Vinh and H. M. Kim, “Electro-spinning fabrication and performance evaluation of polyacrylonitrile nanofiber for air filter applications,” *Appl. Sci.*, vol. 6, no. 9, 2016.
 - [26] C. Burger, B. S. Hsiao, and B. Chu, “Nanofibrous materials and their applications,” *Annu. Rev. Mater. Res.*, vol. 36, no. 1, pp. 333–368, 2006.
 - [27] V. Reza *et al.*, Title,” *Bussiness Law binus*, vol. 7, no. 2, pp. 33–48, 2020.
 - [28] R. Gonçalves *et al.*, “Magnetoelectric CoFe₂O₄/polyvinylidene fluoride electrospun nanofibres,” *Nanoscale*, vol. 7, no. 17, pp. 8058–8061, 2015.
 - [29] T. Danno *et al.*, “Fine structure of PVDF nanofiber fabricated by electrospray deposition,” *J. Polym. Sci. Part B Polym. Phys.*, vol. 46, no. 6, pp. 558–563, 2008.
 - [30] J. G. Bergman, J. H. McFee, and G. R. Crane, “Pyroelectricity and optical second harmonic generation in polyvinylidene fluoride films,” *Appl. Phys. Lett.*, vol. 18, no. 5, pp. 203–205, 1971.
 - [31] W. Lu, Y. Guo, Y. Zhu, and Y. Chen, “Flexible sensors,” *Nanosensors Smart Manuf.*, no. June, pp. 115–136, 2021.
 - [32] V. R. Reddy, “Electrical properties of Au/polyvinylidene fluoride/n-InP Schottky diode with polymer interlayer,” *Thin Solid Films*, vol. 556, pp. 300–306, 2014.
 - [33] A. N. Arshad, M. H. M. Wahid, M. Rusop, W. H. A. Majid, R. H. Y. Subban, and M. D. Rozana, “Dielectric and structural properties of poly(vinylidene fluoride) (PVDF) and poly(vinylidene fluoride-trifluoroethylene) (PVDF-TrFE) filled with magnesium oxide nanofillers,” *J. Nanomater.*, vol. 2019, 2019.
 - [34] P. Taylor and T. Furukawa, “Phase Transitions : A Multinational Ferroelectric properties of vinylidene fluoride copolymers,” *Phase Transitions*, vol. 18, no. January, 1989, pp. 143–211, 1989.
 - [35] V. S. Bystrov, “Molecular modeling and molecular dynamics simulation of the polarization switching phenomena in the ferroelectric polymers PVDF at the nanoscale,” *Phys. B Condens. Matter*, vol. 432, pp. 21–25, 2014.
 - [36] M. Tayyab *et al.*, “Enhanced output in polyvinylidene fluoride nanofibers based triboelectric nanogenerator by using printer ink as nano-fillers,” *Nano Energy*,

vol. 77, no. July, p. 105178, 2020.

- [37] S. Aghayari, *An introduction to PVDF nanofibers properties, and ways to improve them, and reviewing output enhancing methods for PVDF nanofibers nanogenerators*, no. November. 2021.
- [38] M. Li *et al.*, “Revisiting the δ -phase of poly(vinylidene fluoride) for solution-processed ferroelectric thin films,” *Nat. Mater.*, vol. 12, no. 5, pp. 433–438, 2013.
- [39] W. C. Gan, W. H. A. Majid, and T. Furukawa, “Ferroelectric polarization, pyroelectric activity and dielectric relaxation in Form IV poly(vinylidene fluoride),” *Polymer (Guildf.)*, vol. 82, pp. 156–165, 2016.
- [40] K. Asai, M. Okamoto, and K. Tashiro, “Real-time investigation of crystallization in poly(vinylidene fluoride)-based nano-composites probed by infrared spectroscopy,” *Polymer (Guildf.)*, vol. 49, no. 24, pp. 5186–5190, 2008.
- [41] S. Lanceros-Méndez, J. F. Mano, A. M. Costa, and V. H. Schmidt, “FTIR and DSC studies of mechanically deformed β -PVDF films,” *J. Macromol. Sci. - Phys.*, vol. 40 B, no. 3–4, pp. 517–527, 2001.
- [42] J. Wu *et al.*, “Magnetic field induced formation of ferroelectric β phase of poly (vinylidene fluoride),” *Appl. Phys. A Mater. Sci. Process.*, vol. 126, no. 8, pp. 1–6, 2020.
- [43] A. Aliane, M. Benwadih, B. Bouthinon, R. Coppard, F. Domingues-Dos Santos, and A. Daami, “Impact of crystallization on ferro-, piezo- and pyro-electric characteristics in thin film P(VDF-TrFE),” *Org. Electron.*, vol. 25, pp. 92–98, 2015.
- [44] Y.-L. Cheng *et al.*, “We are IntechOpen , the world ’ s leading publisher of Open Access books Built by scientists , for scientists TOP 1 %,” *Intech*, vol. 11, no. tourism, p. 13, 2016, [Online]. Available: <https://www.intechopen.com/books/advanced-biometric-technologies/liveness-detection-in-biometrics>
- [45] R. Crecorio and M. Cestari, “Effect of Temperature on the Crystalline Phase Content and Morphology of Poly (vinylidene Fluoride),” *J. Polym. Sci. Part B Polym. Phys.*, vol. 32, pp. 859–870, 2006.
- [46] J. Jiang *et al.*, “We are IntechOpen , the world ’ s leading publisher of Open Access books Built by scientists , for scientists TOP 1 %,” *Intech*, vol. 34, no.

8, pp. 57–67, 2010.

- [47] R. H. Upadhyay and R. R. Deshmukh, “Investigation of dielectric properties of newly prepared β -phase polyvinylidene fluoride-barium titanate nano-composite films,” *J. Electrostat.*, vol. 71, no. 5, pp. 945–950, 2013.
- [48] L. Priya and J. P. Jog, “Poly(vinylidene fluoride)/clay nano-composites prepared by melt intercalation: Crystallization and dynamic mechanical behavior studies,” *J. Polym. Sci. Part B Polym. Phys.*, vol. 40, no. 15, pp. 1682–1689, 2002.
- [49] R. Gonçalves *et al.*, “Nucleation of the electroactive β -phase, dielectric and magnetic response of poly(vinylidene fluoride) composites with Fe₂O₃ nanoparticles,” *J. Non. Cryst. Solids*, vol. 361, no. 1, pp. 93–99, 2013.
- [50] H. Kawai, “The Piezoelectricity of Poly (vinylidene Fluoride),” *Jpn. J. Appl. Phys.*, vol. 8, no. 7, p. 975, 1969.
- [51] S. S. Choi, Y. S. Lee, C. W. Joo, S. G. Lee, J. K. Park, and K. S. Han, “Electro-spun PVDF nanofiber web as polymer electrolyte or separator,” *Electrochim. Acta*, vol. 50, no. 2-3 SPEC. ISS., pp. 339–343, 2004.
- [52] Y. P. Su, L. N. Sim, X. Li, H. G. L. Coster, and T. H. Chong, “Anti-fouling piezoelectric PVDF membrane: Effect of morphology on dielectric and piezoelectric properties,” *J. Memb. Sci.*, vol. 620, no. July 2020, p. 118818, 2021.
- [53] P. Saxena and P. Shukla, “A comprehensive review on fundamental properties and applications of poly(vinylidene fluoride) (PVDF),” *Adv. Compos. Hybrid Mater.*, vol. 4, no. 1, pp. 8–26, 2021.
- [54] K. Xia, Z. Zhu, H. Zhang, and Z. Xu, “A triboelectric nanogenerator as self-powered temperature sensor based on PVDF and PTFE,” *Appl. Phys. A Mater. Sci. Process.*, vol. 124, no. 8, pp. 1–7, 2018.
- [55] N. Khan, H. Omran, Y. Yao, and K. N. Salama, “Flexible PVDF ferroelectric capacitive temperature sensor,” *Midwest Symp. Circuits Syst.*, vol. 2015-Sept, pp. 21–24, 2015.
- [56] J. Zhao, F. Li, Z. Wang, P. Dong, G. Xia, and K. Wang, “Flexible PVDF nanogenerator-driven motion sensors for human body motion energy tracking and monitoring,” *J. Mater. Sci. Mater. Electron.*, vol. 32, no. 11, pp. 14715–14727, 2021.

- [57] S. A. Pullano, I. Mahbub, S. K. Islam, and A. S. Fiorillo, "PVDF sensor stimulated by infrared radiation for temperature monitoring in microfluidic devices," *Sensors (Switzerland)*, vol. 17, no. 4, 2017.
- [58] S. Gupta, L. Lorenzelli, and R. Dahiya, "Multifunctional flexible PVDF-TrFE/BaTiO₃ based tactile sensor for touch and temperature monitoring," *Proc. IEEE Sensors*, vol. 2017-Decem, pp. 1–3, 2017.
- [59] G. C. Psarras, *Fundamentals of dielectric theories*. Elsevier Inc., 2018. doi: 10.1016/B978-0-12-813215-9.00002-6.
- [60] B. Szigeti, "Dielectric Behavior and Structure by C. P. Smyth," *Acta Crystallogr.*, vol. 9, no. 10, pp. 838–839, 1956.
- [61] "mulvihill1995.pdf."
- [62] J. Baek, T. Isobe, and M. Senna, "Ceramics via a Soft Mechanochemical Route," vol. 81, no. 192422, 1997.
- [63] M. Staiger, P. Bowen, J. Ketterer, and J. Bohonek, "Particle size distribution measurement and assessment of agglomeration of commercial nanosized ceramic particles," *J. Dispers. Sci. Technol.*, vol. 23, no. 5, pp. 619–630, 2002.
- [64] J. F. S. Haitao Huang, *Ferroelectric Materials for Energy*. 2018.
- [65] G. Jaeger, "The ehrenfest classification of phase transitions: Introduction and evolution," *Arch. Hist. Exact Sci.*, vol. 53, no. 1, pp. 51–81, 1998.
- [66] Y. Mnyukh, "Ferroelectric State and Phase Transitions," no. January, pp. 119–130, 2018.
- [67] F. Mokhtari, M. Latifi, and M. Shamshirsaz, "Electro-spinning/electrospray of polyvinylidene fluoride (PVDF): Piezoelectric nanofibers," *J. Text. Inst.*, vol. 107, no. 8, pp. 1037–1055, 2016.

BIOGRAPHY

Wafaa Abdallah Suliman ABKAR completed her high school education at Al Khadra School. She graduated from the Faculty of Science and Technology, Department of Physics Science at Omdurman Islamic University with a grade Excellent with First Honours in 2014. She worked at the Physics Lab as a Teaching Assistant in 2015-2018 at the Faculty of Science and Technology Department of Physics. She won a Turkiye scholarship to Study Master's Degree in 2018. She completed her Master of Science Degree at the Institute of Nanotechnology at Gebze Technical University in 2023.

