

**DEVELOPMENT AND CHARACTERIZATION OF
POLY (VINYLIDENE FLUORIDE) (PVDF)/
POTASSIUM SODIUM NIOBATE (KNN)
NANOCOMPOSITE BASED PIEZOELECTRIC
MATERIALS**

SATYARANJAN BAIRAGI



**DEPARTMENT OF TEXTILE AND FIBRE
ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
JULY 2021**

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by

SATYARANJAN BAIRAGI

Department of Textile and Fibre Engineering

Submitted

In fulfilment of the requirements of the degree of

Doctor of Philosophy

to the



Indian Institute of Technology Delhi

JULY 2021

DEDICATED

TO

Late Shudisankar Dey, My guide and parents

CERTIFICATE

This is to certify that the thesis entitled “**Development and Characterization of Poly (vinylidene Fluoride) (PVDF)/ Potassium Sodium Niobate (KNN) Nanocomposite based Piezoelectric Materials**” being submitted by **Mr. Satyaranjan Bairagi**, to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** in the Department of Textile and Fibre Engineering, is a record of bonafide research work carried out by him. Mr. Bairagi has worked under my guidance and supervision and fulfilled all the requirements for the submission of the thesis.

The results contained in this thesis have not been submitted, in part or full, to any other University or Institute for the award of any degree or diploma.

Dr. S. Wazed Ali

Associate Professor

Department of Textile and Fibre Engineering

Indian Institute of Technology Delhi

Hauz Khas, New Delhi: 110016

India

Acknowledgement

I wish to express my heartiest gratitude and sincere regards to my respectable supervisor, Prof. Wazed Ali for his constant inspiration, encouragement, and invaluable guidance and help that he bestowed on me right from the inception to the successful completion of this endeavor.

I am very much grateful to my SRC members, Prof. Manjeet Jassal, Prof. Rajiv. K. Srivastava and Prof. Sitikantha Roy for their constructive criticism and valuable suggestions. I am also thankful to Prof. Neeraj Khare, Prof. Ratnamala Chatterjee of Physics Department, IIT Delhi for allowing their facilities related to my research studies.

I am thankful to Science and Engineering Research Board (SERB), Department of Science and Technology (DST), Government of India, for financial support to this research work.

I am very much thankful to Late Sudhisankar Dey and Mr. Barun Kumar Halder for their immense support and enthusiasm since my matriculation and henceforth. I owe my professional success in my academic career to beloved Sudhisankar Sir and Barun uncle. A line of gratitude would never suffice to the magnitude of help which I have received from them.

I am indebted to Prof. B.K. Behera, Prof. A.K. Agrawal and Prof. R S Rengasamy as the heads of the textile and fibre engineering department at various stages of my research, allowed me to use all the facilities available in the department and many thanks to all the faculty members, research scholars of the department.

I extend my sincere thanks to Prof. Rajiv K Srivastava, Prof. Bipin Kumar, Mr. Khattar, Mr. Rajkumar, Mr. Amarjeet, Mr. Kala, Mr. Veerender, Mr. Suresh, Mr. Rohit, Mr. Sandeep, Mr. Antriksh, Mr. Surinder, Mr. Biswal, Mr. Rajkumar, Mr. Sulabh, Mr. Kuldeep, Mr. Mahesh, Ms. Aastha, Mr. Jeetender and Mr. Sunny from IIT Delhi.

I would also like to thank my hostel mates Dr. Sarvesh, Mr. Jaswant, Mr. Deepak, Mr. Nitin, Mr. Athar, Mr. Soumya, Mr. Kamal, Mr. Anjeet, Mr. Abhishek, Mr. Arun, Mr. Surya, Mr. Ambuj, Mr. Takley, and Mr. Rajiv.

I would like to express my heartiest thanks and gratitude to all my friends and colleagues for their direct and indirect help. I am especially thankful to Dr. Santanu Basak, Mr. Anupam Chowdhury, Mr. Sourav Banerjee, Mr. Arunabh Agnihotri, Mr. Subhadeep Paul, Mr. Saikat

Ghosh, Mr. Rahul Gadkari, Ms. Swagata Banerjee, Dr. Bapan Adak, Dr. Taruna Bansal, Dr. Anasuya Roy Ghosh, Dr. Aranya Ghosh, Mrs. Doyel Bhattacharyya, Mr. Prasun Mathur, Mr. Indrajeet, Mr. Mayank Agrawal, Dr. Shahadat, Dr. Shahidul Islam, Dr. Mahfooz Khan, Ms. Jayashree Mohanty, Ms. Hema Garg, Ms. Priyanka Gupta, Ms. Shikha Chouhan, Mrs. Mayuri Srivastava, Ms. Juhi Chakraborty, Mr. Sanchayan Pal, Dr. Pratik Samanta, Dr. Jit Pal, Mr. Avinash Raulo, Mr. Anil Yadav, and Mr. Pramod Gurave. I also extend my gratitude to Dr. Hemojit Huidrom Singh and Mr. Hitesh Gulati from Physics department for their timely help.

I am grateful to my parents Mr. Anil Kumar Bairagi and Mrs. Kalpana Bairagi for their immense support which helped to continuously focus on my research without being worried about anything else in the world. Also, the gratitude is extended to my best friend Ms. Debarati Bhattacharyya, and other relatives for their continuous help, support and encouragement.

Finally, I thank everyone who has influenced me to come all the way for doctoral research.

Mr. Satyaranjan Bairagi

Abstract

In the recent era, the mandate of energy in day-to-day life is gradually increasing with the growing population. Hence, emergence of a prudent, most fruitful, low cost and green energy method to fulfil the ever-growing energy demands in the daily life is one of the most promising tasks. Nevertheless, there are different energy sources in the surrounding environment from which energy can easily be harvested such as solar, thermal, chemical, biological and mechanical energies among which the most abundantly found in our ecosystem is mechanical energy. It is obvious that this energy is being debilitated during human body movement, walking, vibration, wind, flow of water and so on. Now-a-days, this accessible energy can be recycled for the use in wireless and portable electronic gadgets where minimal power is required. Generally, a source of power is battery for most of the electronic goods, but it has some circumscriptions. For instance, it has marginal life span. Hence, self-powered techniques naturally get more engrossment to resolve such above stated challenges. In the recent days, piezoelectric energy harvesters are employed to boost up the wireless and portable electronic gadgets. Currently, the only commercially successful piezoelectric polymers are poly (vinylidene fluoride) (PVDF) and its copolymers. PVDF has attractive electroactive properties, such as piezoelectricity, ferroelectricity and pyroelectricity. However, it has low coupling factor (0.30) and the dielectric constant (6 - 10). On the other hand, lead zirconate titanate (PZT) is the commonly used ceramic-based piezoelectric material due to its very lucrative properties like high electromechanical behaviour (coupling factor, 0.7), piezoelectric constant (d_{33} value lies between 250 to 700 pC/N) and the Curie temperature ($>400^{\circ}\text{C}$). But in the recent era, the use of PZT has become limited due to its negative impact towards the environment because of the presence of toxic lead content in its structure (more than 60 wt. % Pb). To overcome the above said problems of PVDF and PZT based piezoelectric materials, in the present thesis work, a lead free

flexible PVDF/potassium sodium niobite (KNN) nanocomposite based piezoelectric materials have been developed by different methods (solution cast, electrospinning, and melt extrusion).

KNN has been chosen as filler material in the present study to develop PVDF polymer-based nanocomposites. As a first step, KNN nanorods have been synthesized via hydrothermal method by varying the process parameters (mole ratio of KOH and NaOH, autoclave filling volume, reaction temperature, and reaction time). The synthesis parameters have been optimised (i.e., 1/5 KOH and NaOH molar ratio, 180 °C reaction temperature, 80% autoclave filling volume) having constant reaction time (8 hours) to achieve KNN nanostructures in the form of nanorods with an average aspect ratio of ~8.5 as calculated by Image J software. Moreover, to confirm the morphological structure of synthesized KNN NRs, SEM analysis has been carried out. In addition, XRD result of the synthesized KNN nanorods has confirmed the orthorhombic crystal structure which has higher piezoelectric properties as per the reported literature. After successful synthesis of KNN nanorods, different nanocomposite based piezoelectric materials have been prepared using KNN nanorods (KNN NRs) as filler materials in PVDF polymer by different methods. At first, PVDF/KNN NRs nanocomposite-based film has been prepared by solution cast method followed by fabrication of piezoelectric nanogenerator. The percentage of KNN nanorods into PVDF matrix has been varied systematically to observe its direct effect on energy harvesting efficiency of the nanogenerator. Interestingly, it has been observed that 10% KNN NRs @ PVDF nanocomposite film possesses the highest electroactive (β -crystal) phase (~98%) as compared to other KNN incorporated samples. In addition, 10% KNN NRs @ PVDF nanocomposite film is capable to generate 3.4 V open circuit voltage and 0.100 μ A current by applying repeated compressive forces on to it. The developed nanogenerator has shown the current density of 0.025 μ A/cm². However, some agglomeration of KNN nanorods has been

observed from the morphological view of the PVDF/KNN based nanocomposite films. To minimize the agglomeration by improving the distribution of KNN NRs throughout the PVDF polymer matrix and to enhance the compatibility between the KNN and PVDF, the surface of KNN NRs has been modified by using surface modifying agents. Herein, KNN nanorods have been surface modified by three diverse surface modifiers such as 3-aminopropyltrimethoxysilane (APS), polyaniline (PANI) and polyvinylpyrrolidone (PVP) for resolving the agglomeration problem of the nanorods and to look for their effects on the micro-structural growth including nucleation of polar crystals of PVDF. The nanocomposite films have been developed simply by solution cast method. The growth of electroactive phases (β and γ) of the PVDF polymer has been observed to be improved significantly by incorporation of surface modified KNN nanorods. The beta fraction ($F(\beta)$) and gamma fraction ($F(\gamma)$) as calculated by the FTIR spectrum (98% and 99%) are maximum for the silane and PVP modified KNN nanorods incorporated PVDF polymer. A PVDF/SM-KNN nanocomposite based nanogenerator has shown ~ 5.6 V output voltage and ~ 0.306 μA current, respectively.

In the next experiment, PVDF/KNN NRs nanocomposite based nano fibrous web has been prepared by electrospinning method. A unique nanogenerator has been fabricated using nanorods (aspect ratio ~ 8.5) of lead-free potassium sodium niobate (KNN) incorporated poly (vinylidene fluoride) (PVDF) based nano fibrous web. The unique dimension of synthesized nanorods with a very low loading (only 3%) have bestowed somewhat surprisingly a negative effect on beta nucleation but subdued this effect by their significant positive contribution towards piezoelectric response by self-orienting the dipoles at the electrospinning process itself. Finally, the developed nanogenerator has showed a higher open circuit output voltage of ~ 17.5 V, output current of ~ 0.522 μA and current density ~ 0.13 $\mu\text{A}/\text{cm}^2$ under a repeated finger tapping and has also able to light up a light emitting diode (LED) of 2 V practically.

Nevertheless, this nanocomposite based fibrous web again shows the distribution issues of the nano fillers inside the matrix like solution cast film. To resolve this problem, silane modified potassium sodium niobate (SM-KNN) has been incorporated in poly (vinylidene fluoride) (PVDF) for developing PVDF/SM-KNN electrospun nanogenerator. PVDF/3% SM-KNN nanocomposite has generated remarkably high output voltage of ~ 21 V, output current of ~ 22 μA , current density of ~ 5.5 $\mu\text{A}/\text{cm}^2$ and power density of ~ 115.5 $\mu\text{W}/\text{cm}^2$. For further improving the piezoelectric performance, other semiconductive (ZnO) and conductive (CNT) fillers have also been added along with KNN nanorods in the PVDF polymer. The output voltage and current for the PVDF/KNN/ZnO based nanogenerator have been noted as ~ 25 V and 1.81 μA (when pressure is applied by the finger tapping mode) and 8.31 V and 5 μA (when pressure is applied by a sewing machine). A power density of 11.31 $\mu\text{W}/\text{cm}^2$ (finger tapping mode) and 10.38 $\mu\text{W}/\text{cm}^2$ (pressure applied by a sewing machine) have also been recorded as exhibited by this nanogenerator. Whereas, in the case of PVDF/KNN/CNT based nanogenerator, 0.1% incorporation of CNT in the nanogenerator has demonstrated a significant improvement in piezoelectric performance with an output voltage of ~ 23.24 V, current ~ 9 μA and power density of 52.29 $\mu\text{W}/\text{cm}^2$ on finger tapping vis-à-vis voltage of ~ 12 V, current of ~ 18 μA and power density of 54 $\mu\text{W}/\text{cm}^2$ on the application of mechanized compressive force.

In a separate study, a flexible nanogenerator based on melt-spun nanocomposite filament has also been successfully prepared. A nanogenerator has been made of PVDF/4% KNN NRs based filament which has exhibited the highest $F(\beta)$ value (i.e., 26% polar β phase). The PVDF/4% KNN NRs filament based nanogenerator could also generate around 3.7 V voltage and 0.326 μA current, respectively.

Finally, the structural characteristics, morphology, and piezoelectric performance of various nanogenerators fabricated by different methods (solution cast, electrospinning, and melt-

extrusion) have been compared. At the end, it has been concluded that the electrospinning method (wherein the best piezoelectric performance has been achieved) is the best technique for developing PVDF/KNN NRs nanocomposite based flexible piezoelectric materials as compared to solution cast and melt extrusion processes.

Keywords: lead-free; flexible; poly (vinylidene difluoride) (PVDF); potassium sodium niobate (KNN); nanocomposites; solution cast; electrospinning; melt extrusion; piezoelectric energy harvesting; nanogenerator

सार

हाल के युग में, बढ़ती जनसंख्या के साथ दैनिक जीवन में ऊर्जा का जनादेश धीरे-धीरे बढ़ रहा है। इसलिए, दैनिक जीवन में लगातार बढ़ती ऊर्जा मांगों को पूरा करने के लिए एक विवेकपूर्ण, सबसे उपयोगी, कम लागत और हरित ऊर्जा पद्धति का उदय सबसे आशाजनक कार्यों में से एक है। फिर भी, आसपास के वातावरण में विभिन्न ऊर्जा स्रोत हैं जिनसे ऊर्जा आसानी से प्राप्त की जा सकती है जैसे सौर, तापीय, रासायनिक, जैविक और यांत्रिक ऊर्जा जिनमें से सबसे अधिक हमारे पारिस्थितिक तंत्र में प्रचुर मात्रा में पाई जाने वाली यांत्रिक ऊर्जा है। यह स्पष्ट है कि यह ऊर्जा मानव शरीर की गति, चलने, कंपन, हवा, पानी के प्रवाह आदि के दौरान दुर्बल हो रही है। आजकल, इस सुलभ ऊर्जा को वायरलेस और पोर्टेबल इलेक्ट्रॉनिक गैजेट्स में उपयोग के लिए पुनर्नवीनीकरण किया जा सकता है जहां न्यूनतम बिजली की आवश्यकता होती है। आम तौर पर, अधिकांश इलेक्ट्रॉनिक सामानों के लिए बिजली का स्रोत बैटरी होता है, लेकिन इसकी कुछ सीमाएं होती हैं। उदाहरण के लिए, इसका सीमांत जीवन काल है। इसलिए, ऊपर बताई गई चुनौतियों को हल करने के लिए स्व-संचालित तकनीक स्वाभाविक रूप से अधिक तल्लीन हो जाती है। हाल के दिनों में, वायरलेस और पोर्टेबल इलेक्ट्रॉनिक गैजेट्स को बढ़ावा देने के लिए पीजोइलेक्ट्रिक एनर्जी हार्वेस्टर का उपयोग किया जाता है। वर्तमान में, केवल व्यावसायिक रूप से सफल पीजोइलेक्ट्रिक पॉलिमर पॉली (विनाइलिडीन फ्लोराइड) (PVDF) और इसके कॉपोलिमर हैं। PVDF में आकर्षक इलेक्ट्रोएक्टिव गुण हैं, जैसे कि पीजोइलेक्ट्रिकिटी, फेरोइलेक्ट्रिकिटी और पायरोइलेक्ट्रिसिटी। हालांकि, इसमें कम युग्मन कारक (0.30) और ढांकता हुआ स्थिरांक (6 - 10) है। दूसरी ओर, उच्च विद्युत यांत्रिक व्यवहार (युग्मन कारक, 0.7), पीजोइलेक्ट्रिक स्थिरांक (d_{33} मान 250 से 700 pC / N के बीच होता है) जैसे बहुत ही आकर्षक गुणों के कारण लेड जिंकोनेट टाइटेनेट (PZT) आमतौर पर इस्तेमाल किया जाने वाला सिरेमिक-आधारित पीजोइलेक्ट्रिक सामग्री है।) और क्यूरी तापमान ($>400^{\circ}\text{C}$)। लेकिन हाल के युग में, इसकी संरचना में विषाक्त सीसा सामग्री (60 wt.% Pb से

अधिक) की उपस्थिति के कारण पर्यावरण पर इसके नकारात्मक प्रभाव के कारण PZT का उपयोग सीमित हो गया है। पीवीडीएफ और पीजेडटी आधारित पीजोइलेक्ट्रिक सामग्री की उपरोक्त समस्याओं को दूर करने के लिए, वर्तमान थीसिस कार्य में, विभिन्न तरीकों (सॉल्यूशन कास्ट, इलेक्ट्रोस्पिनिंग और मेल्ट) द्वारा एक लीड फ्री फ्लेक्सिबल पीवीडीएफ/पोटेशियम सोडियम नाइओबाइट (केएनएन) नैनोकम्पोजिट आधारित पीजोइलेक्ट्रिक सामग्री विकसित की गई है। बाहर निकालना)।

पीवीडीएफ पॉलीमर-आधारित नैनोकम्पोजिट विकसित करने के लिए केएनएन को वर्तमान अध्ययन में भराव सामग्री के रूप में चुना गया है। पहले चरण के रूप में, KNN नैनोरोड्स को हाइड्रोथर्मल विधि के माध्यम से प्रक्रिया मापदंडों (KOH और NaOH के मोल अनुपात, आटोक्लेव फिलिंग वॉल्यूम, प्रतिक्रिया तापमान, रिक्शन टाइम) को अलग करके संश्लेषित किया गया है। संश्लेषण मापदंडों को अनुकूलित किया गया है (यानी, 1/5 KOH और NaOH दाढ़ अनुपात, 180 °C प्रतिक्रिया तापमान, 80% आटोक्लेव भरने की मात्रा) जिसमें निरंतर प्रतिक्रिया समय (8 घंटे) होता है ताकि KNN नैनोस्ट्रक्चर को औसत पहलू के साथ नैनोरोड के रूप में प्राप्त किया जा सके। इमेज जे सॉफ्टवेयर द्वारा परिकलित ~8.5 का अनुपात। इसके अलावा, संश्लेषित KNN NRs की रूपात्मक संरचना की पुष्टि करने के लिए, SEM विश्लेषण किया गया है। इसके अलावा, संश्लेषित केएनएन नैनोरोड्स के एक्सआरडी परिणाम ने ऑर्थोरोम्बिक क्रिस्टल संरचना की पुष्टि की है जिसमें रिपोर्ट किए गए साहित्य के अनुसार उच्च पीजोइलेक्ट्रिक गुण हैं। केएनएन नैनोरोड्स के सफल संश्लेषण के बाद, विभिन्न तरीकों से पीवीडीएफ पॉलिमर में भराव सामग्री के रूप में केएनएन नैनोरोड्स (केएनएन एनआर) का उपयोग करके विभिन्न नैनोकम्पोजिट आधारित पीजोइलेक्ट्रिक सामग्री तैयार की गई है। सबसे पहले, PVDF/KNN NRs नैनोकम्पोजिट-आधारित फिल्म को सॉल्यूशन कास्ट विधि द्वारा तैयार किया गया है जिसके बाद पीजोइलेक्ट्रिक नैनोजेनरेटर का निर्माण किया गया है। पीवीडीएफ मैट्रिक्स में केएनएन नैनोरोड्स के प्रतिशत को नैनोजेनरेटर की ऊर्जा संचयन दक्षता पर इसके प्रत्यक्ष प्रभाव का निरीक्षण करने

के लिए व्यवस्थित रूप से विविध किया गया है। दिलचस्प बात यह है कि यह देखा गया है कि 10% केएनएन एनआर @ पीवीडीएफ नैनोकम्पोजिट फिल्म में अन्य केएनएन शामिल नमूनों की तुलना में उच्चतम इलेक्ट्रोएक्टिव (β -क्रिस्टल) चरण ($\sim 98\%$) है। इसके अलावा, 10% केएनएन एनआर @ पीवीडीएफ नैनोकम्पोजिट फिल्म बार-बार कंप्रेसिव फोर्स लगाकर 3.4 वी ओपन सर्किट वोल्टेज और $0.100 \mu\text{A}$ करंट उत्पन्न करने में सक्षम है। विकसित नैनोजेनरेटर ने $0.025 \mu\text{A}/\text{cm}^2$ का वर्तमान घनत्व दिखाया है। हालांकि, केएनएन नैनोरोड्स के कुछ समूह को पीवीडीएफ/केएनएन आधारित नैनोकम्पोजिट फिल्मों के रूपात्मक दृष्टिकोण से देखा गया है। पीवीडीएफ पॉलिमर मैट्रिक्स में केएनएन एनआर के वितरण में सुधार करके और केएनएन और पीवीडीएफ के बीच संगतता को बढ़ाने के लिए, केएनएन एनआर की सतह को सतह संशोधित एजेंटों का उपयोग करके संशोधित किया गया है। इसके साथ ही, केएनएन नैनोरोड्स को तीन विविध सतह संशोधकों द्वारा संशोधित किया गया है जैसे कि 3-एमिनोप्रोपाइलट्रिमेथॉक्सीसिलेन (एपीएस), पॉलीएनिलिन (पैनआई) और पॉलीविनाइलपाइरोलिडोन (पीवीपी) नैनोरोड्स की ढेर समस्या को हल करने और सूक्ष्म-संरचनात्मक पर उनके प्रभावों को देखने के लिए। पीवीडीएफ के ध्रुवीय क्रिस्टल के न्यूक्लियेशन सहित विकास। नैनोकम्पोजिट फिल्मों को केवल सॉल्यूशन कास्ट विधि द्वारा विकसित किया गया है। पीवीडीएफ पॉलिमर के इलेक्ट्रोएक्टिव चरणों (β और γ) की वृद्धि को सतह संशोधित केएनएन नैनोरोड्स के समावेश से काफी सुधार हुआ देखा गया है। बीटा अंश ($F(\beta)$) और गामा अंश ($F(\gamma)$) जैसा कि FTIR स्पेक्ट्रम (98% और 99%) द्वारा परिकलित किया गया है, सिलेन और PVP संशोधित KNN नैनोरोड्स में PVDF पॉलिमर को शामिल करने के लिए अधिकतम हैं। एक PVDF/SM-KNN नैनोकम्पोजिट आधारित नैनोजेनरेटर ने क्रमशः $\sim 5.6 \text{ V}$ आउटपुट वोल्टेज और $\sim 0.306 \mu\text{A}$ करंट दिखाया है।

अगले प्रयोग में, PVDF/KNN NRs नैनोकम्पोजिट आधारित नैनो रेशेदार वेब इलेक्ट्रोसपिनिंग विधि द्वारा तैयार किया गया है। लेड-फ्री पोटेशियम सोडियम नाइओबेट (केएनएन) निगमित पॉली (विनाइलिडीन

फ्लोराइड) (पीवीडीएफ) आधारित नैनो रेशेदार वेब के नैनोरोड्स (पहलू अनुपात ~ 8.5) का उपयोग करके एक अद्वितीय नैनोजेनरेटर तैयार किया गया है। बहुत कम लोडिंग (केवल 3%) के साथ संश्लेषित नैनोरोड्स के अद्वितीय आयाम ने बीटा न्यूक्लियेशन पर कुछ हद तक आश्चर्यजनक रूप से नकारात्मक प्रभाव डाला है, लेकिन इलेक्ट्रोस्पिनिंग प्रक्रिया में द्विध्रुवों को स्व-उन्मुख करके पीजोइलेक्ट्रिक प्रतिक्रिया के प्रति उनके महत्वपूर्ण सकारात्मक योगदान से इस प्रभाव को कम कर दिया है। अंत में, विकसित नैनोजेनरेटर ने बार-बार फिंगर टैपिंग के तहत ~ 17.5 V का एक उच्च ओपन सर्किट आउटपुट वोल्टेज, ~ 0.522 μA का आउटपुट करंट और करंट डेंसिटी ~ 0.13 $\mu\text{A}/\text{cm}^2$ दिखाया है और एक प्रकाश उत्सर्जक डायोड (एलईडी) को भी रोशन करने में सक्षम है।) 2 वी व्यावहारिक रूप से। फिर भी, यह नैनोकम्पोजिट आधारित रेशेदार वेब फिर से मैट्रिक्स के अंदर नैनो फिलर्स के वितरण मुद्दों को दिखाता है जैसे सॉल्यूशन कास्ट फिल्म। इस समस्या को हल करने के लिए, पीवीडीएफ/एसएम-केएनएन इलेक्ट्रोस्पुन नैनोजेनरेटर विकसित करने के लिए पॉली (विनाइलिडीन फ्लोराइड) (पीवीडीएफ) में सिलेन संशोधित पोटेशियम सोडियम निबोएट (एसएम-केएनएन) को शामिल किया गया है। PVDF/3% SM-KNN नैनोकम्पोजिट ने उल्लेखनीय रूप से उच्च आउटपुट वोल्टेज ~ 21 V, आउटपुट करंट ~ 22 μA , करंट डेंसिटी ~ 5.5 $\mu\text{A}/\text{cm}^2$ और पावर डेंसिटी ~ 115.5 $\mu\text{W}/\text{cm}^2$ जेनरेट किया है। पीजोइलेक्ट्रिक प्रदर्शन को और बेहतर बनाने के लिए, पीवीडीएफ पॉलीमर में केएनएन नैनोरोड्स के साथ अन्य सेमीकंडक्टिव (जेडएनओ) और कंडक्टिव (सीएनटी) फिलर्स भी जोड़े गए हैं। PVDF/KNN/ZnO आधारित नैनोजेनरेटर के लिए आउटपुट वोल्टेज और करंट को ~ 25 V और 1.81 μA (जब फिंगर टैपिंग मोड द्वारा दबाव लागू किया जाता है) और 8.31 V और 5 μA (जब एक सिलाई मशीन द्वारा दबाव लागू किया जाता है) के रूप में नोट किया गया है) । इस नैनोजेनरेटर द्वारा प्रदर्शित 11.31 $\mu\text{W}/\text{cm}^2$ (उंगली टैपिंग मोड) और 10.38 $\mu\text{W}/\text{cm}^2$ (सिलाई मशीन द्वारा लागू दबाव) की शक्ति घनत्व भी दर्ज की गई है। जबकि, PVDF/KNN/CNT आधारित नैनोजेनरेटर के मामले में, नैनोजेनरेटर में CNT के

0.1% समावेश ने ~ 23.24 V के आउटपुट वोल्टेज, वर्तमान $\sim 9 \mu\text{A}$ और $52.29 \mu\text{W}$ के पावर घनत्व के साथ पीजोइलेक्ट्रिक प्रदर्शन में एक महत्वपूर्ण सुधार का प्रदर्शन किया है। ~ 12 वी के वोल्टेज के साथ-साथ उंगली टैपिंग पर सेमी², मशीनीकृत संपीड़न बल के आवेदन पर $\sim 18 \mu\text{A}$ की वर्तमान और $54 \mu\text{W}/\text{cm}^2$ की शक्ति घनत्व।

एक अलग अध्ययन में, मेल्ट-स्पून नैनोकम्पोजिट फिलामेंट पर आधारित एक लचीला नैनोजेनरेटर भी सफलतापूर्वक तैयार किया गया है। PVDF/4% KNN NRs आधारित फिलामेंट से एक नैनोजेनरेटर बनाया गया है जिसने उच्चतम $F(\beta)$ मान (यानी, 26% ध्रुवीय β चरण) प्रदर्शित किया है। PVDF/4% KNN NRs फिलामेंट आधारित नैनोजेनरेटर भी क्रमशः लगभग 3.7 V वोल्टेज और $0.326 \mu\text{A}$ करंट उत्पन्न कर सकता है।

अंत में, विभिन्न तरीकों (समाधान डाली, इलेक्ट्रोसपिनिंग, और पिघल-एक्सट्रूज़न) द्वारा निर्मित विभिन्न नैनोजेनरेटरों की संरचनात्मक विशेषताओं, आकारिकी और पीजोइलेक्ट्रिक प्रदर्शन की तुलना की गई है। अंत में, यह निष्कर्ष निकाला गया है कि इलेक्ट्रोसपिनिंग विधि (जिसमें सबसे अच्छा पीजोइलेक्ट्रिक प्रदर्शन हासिल किया गया है) PVDF/KNN NRs नैनोकम्पोजिट आधारित लचीली पीजोइलेक्ट्रिक सामग्री को सॉल्यूशन कास्ट और मेल्ट एक्सट्रूज़न प्रक्रियाओं की तुलना में विकसित करने के लिए सबसे अच्छी तकनीक है।

कीवर्ड: सीसा रहित; लचीला; पाली (विनाइलिडीन डिफ्लुओराइड) (PVDF); पोटेशियम सोडियम नाइओबाइट (केएनएन); नैनोकंपोजिट; समाधान डाली; विद्युत कटाई; पिघल बाहर निकालना; पीजोइलेक्ट्रिक ऊर्जा संचयन; नैनोजेनरेटर

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List of Acronyms

PVDF-	Poly (vinylidene difluoride)
P-PVDF-	Pure Poly (vinylidene difluoride)
KNN-	Potassium Sodium Niobate
KOH-	Potassium Hydroxide
NaOH-	Sodium Hydroxide
DMF-	Dimethylformamide
PANI-	Polyaniline
PVP-	Polyvinylpyrrolidone
APS-	3-aminopropyltrimethoxysilane
PP-	Polypropylene
PDMS-	Polydimethylsiloxane
PTFE-	Polytetrafluoroethylene
SM KNN-	Silane Modified Potassium Sodium Niobate
PM KNN-	Polyaniline Modified Potassium Sodium Niobate
PV KNN-	Polyvinyl pyrrolidone Modified Potassium Sodium Niobate
UT-KNN-	Untreated Potassium Sodium Niobate
ZnO-	Zinc Oxide
CNT-	Carbon Nanotube
XRD-	X-ray Diffraction
FTIR-	Fourier Transform Infra-Red
SEM-	Scanning Electron Microscope
TEM-	Transmission Electron Microscope
SAED	Selected Area Electron Diffraction
EDX-	Energy Dispersive X-Ray
HRTEM	High Resolution Transmission Electron Microscope
TGA-	Thermal Gravimetric Analysis
DSC-	Differential Scanning Calorimetry
LCR-	Inductance Capacitance Resistance
P-E-	Polarization Electric- Field
DC-	Direct Current
AC-	Alternating Current
DI-	Deionised
EH-	Energy Harvesting
SCF-	Solution Cast Film
MSF-	Melt Spun Filament
ESW-	Electrospun Web
PZT-	Lead Zirconate Titanate
NRs-	Nanorods
EIA-	Energy Information Administration
PENG-	Piezoelectric Nanogenerator
Cm-	Centimetre
kV-	Kilo Volt
g-	Gram
V-	Voltage
R-	Resistance
P-	Power
P _d -	Power Density

I-	Current
I _d -	Current Density
F (β)-	Beta Fraction
°C-	Degree Centigrade
μA-	Micro Ampere
μW-	Micro Watt
LED-	Light Emitting Diode