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THEORETICAL INVESTIGATION OF THE COMPACT DIELECTRIC POLYMER USING PVDF-HFP

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ABSTRACT

Reducing the size of the dielectric material is a big problem to prepare next-generation dielectric gadget. In this paper, we proposed solution of this problem that affects the size of the dielectric particles. Due to the large size of 140nm, a good permittivity has been detected. This has been explained by the property of a material like structure, model, lattice size, or shape and having a very large permittivity. We observed the permittivity for the approx. size of about 1.1µm, due to the domain – wall role and boundary effect. The proposed work will highlight necessity to make devices that have a very small size and may give very large production with the help of PVDF-HFP.

Keywords: PVDF-HFP, Dielectric Polymer.

INTRODUCTION

In the present time, the dielectric polymer is a widely researched area of people's focus. Dielectric polymers are used to make many artificial electronic devices like sensors, insulated cables, wires, electronic kits, etc. and in the present time, maximum work has been done by these devices. For making the dielectric polymers, we require a very high thermal conducting polymer at a very low cost. Dielectric polymers depend upon the size and materials; this form of scale is known as the size effect. We all know about the general concept of dielectric polymers it's just like insulators but when we give an electric field then the current doesn't flow in the circuit because all metals don't have free electrons in their outermost shell due to this polarization occurring. The positive charge particles move towards the electric field per minute and the negative charge particles move opposite in direction of the electric field that separates charge and polarization that reducing the electric field. It is based on the dielectric constant, electric susceptibility, dielectric polarization, and dielectric breakdown. The difference in the ratio of the permittivity of the free space is called the dielectric constant. Those substances have high permittivity then they can store more energy however, to make a high-energy storage device is expected to show a large density and maximum energy loss. Based on the principle, we make a low-size capacitor that gives more energy to vehicles' dielectric polymers depending upon the polarization. This depends upon its properties like size and structure. Moreover, we can modify their property by adding inorganic materials like as PVA, Poly (vinylidene fluoride-hexafluoropropylene) (PVDF-HFP), PMMA, PAN, CNF, etc. In this paper, we take Poly(vinylidene fluoride-hexafluoropropylene) as filler. PVDF is a semi-crystalline polymer that has a high electric coefficient and good thermal, physical, and chemical stability, it is made up of copolymers such as [PVDF-TrFE] and [PVDF-TrFE-CFE] posted to fabricate and have high electric composites. But Poly (vinylidene fluoride-hexafluoropropylene) has one of the biggest disadvantages which are a high volume fraction of the filler that is needed to fabricate high electric composition. At that time, two policy developed by the analyzer for the dielectric permittivity. One is ceramic fillers react with very high dielectric constant with the polymer and 2nd is conductive fillers are carbon material or conductive polymers. When more polymers are combined then it has high breakdown strength which affects flexibility. But Poly (vinylidene fluoride-hexafluoropropylene) has one of the biggest disadvantages that have a large volume fraction of the fillers is needed for fabricate high electric composition. Many projects and models have demonstrated that high-side ratio fillers can retouch the electric constant of the composition[1-3]

DIELECTRIC FILLER BaTiO3 REACT WITH NANOSOLID PARTICLES COMPOSITION

At that time many different methods have been made to make polymers with high dielectric constant nanoparticles into a polymer at a maximum dielectric constant and minimum dielectric loss. When we take aimaginary Barium titanate (BaTiO3) nanofiber via electro spinning Barium titanate (BaTiO3) nanofibers. The result is that a united field with BaTiO3 nanofibers presents a high dielectric constant and greater breakdown strength than the compound with BaTiO3 nanoparticles. This method or way used by many researchers to make a composite with dielectric constant but the compounds fill with more ratio fillers until investigated at a large scale. Those who have spherical fillers because of dare in making nano solid things like wires, and machinery parts. Here many researchers have presented their theory based on nano solid materials of the dielectric constant, its mechanical and physical properties of material and the energy storage of the dielectric polymer. Here we announce a mixed approach for the dielectric property of the polymer. Polyvinylidene fluoride-hexafluoropropylene is posted as a polymer metric. Barium titanate (BaTiO3) nanofibers through the hydrothermal method are used as dielectric fillers. The main aim of this paper is to get great energy composites with low pot contents. The role of BaTiO3 in nano solid materials increased the dielectric constant of the compounds with low pot contents.[2-4]

Finally, the resulting focus on the dielectric constant in Poly (vinylidene fluoride-hexafluoropropylene)/ Barium titanate nano materials compounds is shown through this process. The fabrication process of BaTiO3 nonmaterials is very easy and takes very less time. Through this process, we can make high-energy capacitors in the future. If we want to see the shape, size, and structure of a nano-particle then we can see it with the help of SEM and TEM images of the BaTiO3 nanowires was got in instruments. We can check the result through XRD (X-Ray Diffraction), SEM, and TEM. The BaTiO3 fillers are successfully set with Poly(vinylidene fluoride-hexafluoropropylene) metrics, with increasing BaTiO3, the dielectric constant is very high.

DIELECTRIC POLYMER (PVDF-HFP) ELECTROLYTE FILMS WITH ELECTRON BEAM

The effects of radiation on the dielectric polymer depend upon many factors like as specific types of radiation, radiation energy, thermal stability, and physical and chemical property of polymers. At present time, many researchers try to modify the properties of the polymer. We have many radiation energy forms like as X-Ray, Gamma Ray, Beta Ray, Electron bean, Sunlight, etc. The electron beam is used to develop a technique for pollution-free use to improve the property of the polymer. The degree of a crystalline polymer has decreased in most of the semi-crystalline polymers at high radiations. The polymers after separation of high energy can present high performance and that used in sensors or transducer appliances. The irradiated polymers were described by using various techniques like AFM (Atomic Force Microscopy), SEM, X-Ray, etc. AFM is an image-conducting or semiconducting surface. It identifies the surface of many polymers like metals, nonmetals, and dry solutions. It also identifies the surface, shape, and size structure of a polymer before and after radiation which was studied by AFM.

EXPERIMENTS

PREPARATION OF THE P(VDF-HFP) FILMS

First of all Dimethylformamide (DMP), Dimethylacetamide, Dimethyl sulpoxide, N-methyl pyrrolidone, a solvent with a 15wt% was dissolved in Poly(vinylidene fluoride-hexafluoropropylene. Now, we continuously convulse for 24 hours at room temp till it totally dissolved. Then, Poly (Vinylidene fluoride-hexafluoropropylene) films formed through this solution costing method that put glass substance and width of Poly vinylidene fluoride-hexafluoropropylene (PVDF-HFP) film manage through the altitude of the film grader. At last, we remove this sample from the solvent and put it at 60ºC for 12 hours. After 12 hours we see that solvent is completely vaporized, then cool the film at room temperature and finally measure the substance.

CHARACTERIZATION AND PROPERTIES MEASUREMENTS

The crystalline property of a Poly (Vinylidene fluoride-hexafluoropropylene) film was identified by X-ray diffraction, Fourier transforms infrared spectroscopy, and differential scanning calorimeter. If we find out the surface microstructure of the metal then, we can identify its SEM setup. With the help of a magnetic induction thickness meter, we can measure the thickness of the film. Before testing the sample, the aluminum electrode was vaporized at the surface of the sample with the help of vacuum coating equipment. Dielectric spectra were estimated with the help of a precision impedance analyzer from 100HZ to 1MHZ. the less amount of current in films has been calculated with the help of a ferroelectric tester

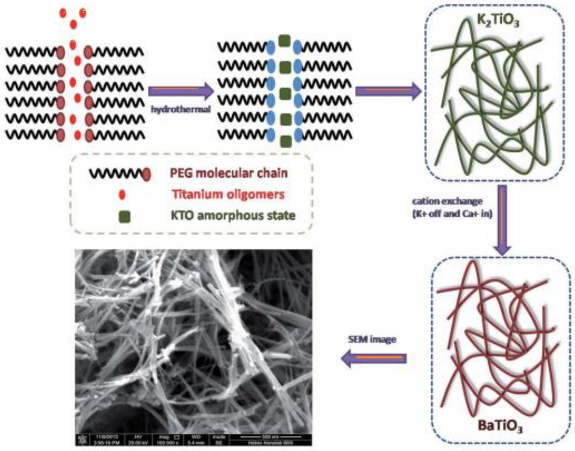

Fig.1: Structure diagram of the preparation of BaTiO3nanowires

The SEM observation has been performed on a "Helios Nanolab 600i". The samples have been arranged by fracturing the composites at liquid nitrogen temperature.[4-6]

SCANNING ELECTRON MICROSCOPE (SEM)

SEM is used to verify the texture, structure, size, and orientation of material and prepare the sample energy dispersive spectroscopy (EDS). This can be used for both quantitative as well as qualitative analysis of the element present in the sample. The interchange of electrons ray with molecules or atoms which have various depths within the sample produce discrete such as secondary electrons, characteristics X-Ray, absorbed current, and transmitted electrons. This is used in SEM to make an image. Discovering all signals is very difficult. By the instrument in SEM, we can deduct the secondary electrons. In the secondary image, these are emitted from very near to the surface. The electrons that are reflected from the sample by elastic scattering are called backscattered electrons. When the Backscattering electrons (BSE) resolve is less than the secondary electron that held its origin from a lower location within the specimen. The intensity of the Backscattering electrons (BSE) signals and the atomic number of the specimen are strongly related to each other. Throw the BSE image can be used to get the distribution of the different samples in the sample.[6-9]the sample in power and metallic palate can be used for SEM analysis. SEM image we can show in the Figure 2.

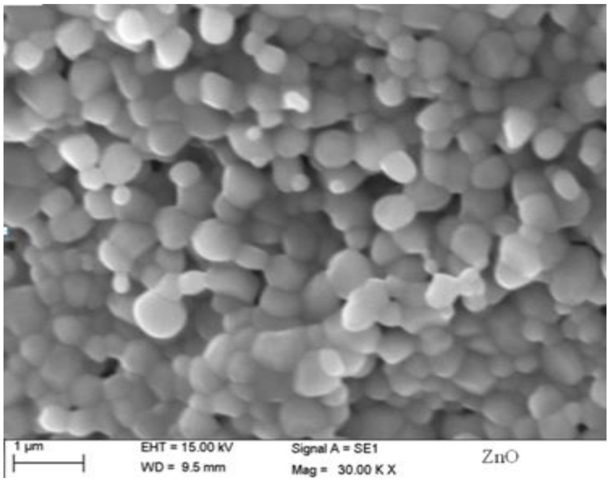

Fig.2: scanning electron microscope for nanoparticles

Energy-dispersive spectroscopy (EDS) is used to find the element information, atomic property, and weight percentage in the sample. The EDS calculates the energy of the x-ray emitted from a specimen that appears difference in energy of the x-ray between the lower energy shell and the higher shell. Therefore, EDS allows the elemental property of the specimen to be a measure[7].

X-RAY DIFFRACTION (XRD)

It happens when any electromagnetic radiation interrelates with periodic structure. The distance of the periodic structure has the same wavelength of the radiation. The wavelength of the x-ray on the order of 1 angstrom = 0.1nm. That is interring atomic distance in crystalline solid, creating an x-ray right order of magnitude for diffraction of atoms of crystalline materials. When an x-ray is reflected from a surface, it can produce a diffracted beam. Bragg's law and Debye- Scherer's formula play very important roles in x-ray diffraction. According to Bragg's law when incident beams of x-ray, which have a wavelength (λ) fall on a crystalline surface that has an angle (θ). The incident angle and reflection angle is the same.8-11 According to Bragg's law

$$2d\sin\theta = n\lambda$$

Here, λ is the wavelength, d is the interpolation distance, θ is the incident angle and reflected beam angle of the x-ray, and n is the integer that represent the order of the diffraction peak.

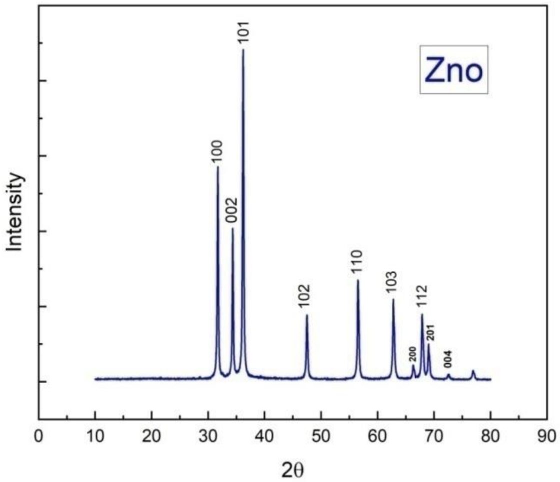

Fig. 3: the XRD pattern of processed silicon nanoparticles

The average crystalline size can be calculated by using Debye- Scherer's formula.

$$D = \frac{\lambda K}{\beta COS\theta}$$

Here, λ is the wavelength (1.54), k is the constant shape factor (0.94), θ is the angle, and β is the Full-Width Half Maximum. Figure 4 shows the diffraction peak [5-13].

$$R = 5\lambda/8\mathrm{Sin}\Theta$$

$$\varepsilon = \beta\mathrm{Cos}\Theta/4$$

Using Debye- Scherer's equation θ is the sharp peak value, R is the average crystallite separation, ε is the strain, D is the crystallite size.

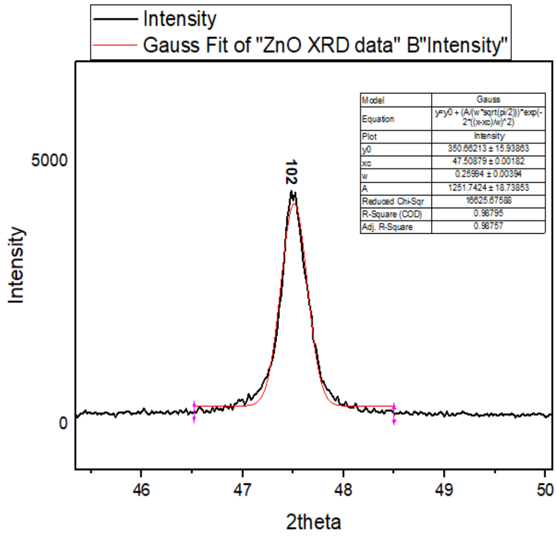

Fig.4: show the diffraction peak makes between intensity and Bragg angle (2θ) by XRD method

The graph plotted between intensity and the angle at which incident or reflected ray come in metallic surface. In graph Figure3.We have many peaks that represent the intensity of the x-ray. Now, we will zoom any one peak, with the help of a data detector we analyze the data with curve fitting and select the gauss method then select fit you got as a result like a Figure 4

DIELECTRIC PROPERTIES OF P(VDF-HFP) COMPOSITES

"Dielectric constant (ε′) and dielectric loss (ε″) curves of the pure Poly(vinylidene fluoride-hexafluoropropylene) co-polymer and its composites as a function of frequency at a constant temperature of 20°C". It can be seen that the composites have higher values of dielectric constant than the pure matrix. The dielectric loss ε'' explain decadence in a dielectric polymer through conduction, low polarization currents for a composition, ε'' can be stated by the calculation

$$\varepsilon'' = \varepsilon''dc + \varepsilon''MW + \varepsilon''D$$

where ε''dc and ε''Mw are associated to "conduction loss" and "interfacial polarization loss", ε''Ddenotes the dipole loss factor. "The conduction loss factors ε''dc and interfacial polarization loss factor ε''MW are given by

$$\varepsilon''dc = \sigma/2\pi f$$

Here, σ and current represent the direct current and frequency". According to the previous equation log ε''dc versus log f represents a straight line

$$\varepsilon''MW\ \alpha\ (\ 1+ K/(1+(2\pi f)\hat{}2\ r2)\ )$$

Here, k is representing the dielectric constant of the film at the interface and r is the relaxation time of polarization [13-17]

The dipole loss factor is used to identify the energy gain in the medium when electromagnetic wave pass through it. When a dielectric material in mixed electric domain is heated then the loss of energy is known as dielectric loss. Dielectric loss is measured by the loss tangent or tan delta (tanᘔ). tanᘔ is the angle between field vector and material loss so, the value of tanᘔ is high than significance the dielectric loss should be.

Loss tangent (tanᘔ) is a dimensionless quantity. It is used to calculate the loss of signals because of elements dissolution of electromagnetic energy that takes place in the sample.

$$\tan Ȣ = \cot\theta = 1/2\pi RpCp$$

Here, tanȢ is the loss angle, θ is the phase angle, f is the frequency, Rp is the equivalent parallel resistance, Cpis the equivalent parallel capacitance

$$\tan Ȣ = \varepsilon''/\varepsilon'$$

Quality factor (Q) is the ratio between stored energy in resonates to the loss of energy in one radiation of the cycle of oscillation. It is a dimensionless quantity.

$$Q = 1/\tan Ȣ$$

ε” is the dielectric loss factor. When we study about the dielectric characteristics of Poly(vinylidene fluoride-hexafluoropropylene) then, we see that the dielectric loss decrease then increase frequency. This occurrence is due to the dipole polarization relaxation at frequencies$^{16-17}$.

All four materials show in figure 5(a) those have similar frequency dependence of the dielectric constant, i.e. the dielectric constant increases with decreasing frequency from 106 to 10-1 Hz. The increase in ε' is particularly strong in the low-frequency range (0.1 -10 Hz) due to polarization effects. In composite materials, both components contribute to the effective dielectric constant of the composite.

In figure 5(b) we can see the dielectric loss at low or high frequency. At first tanȢ downfall and then increase as the frequency gets higher. In this span emplacement of dipole polarization can’t follow the electric field so, the polarization relaxation show to enhanced loss. The tanȢ composition is lower than polymer and it does continue to decrease when the filler content increase.

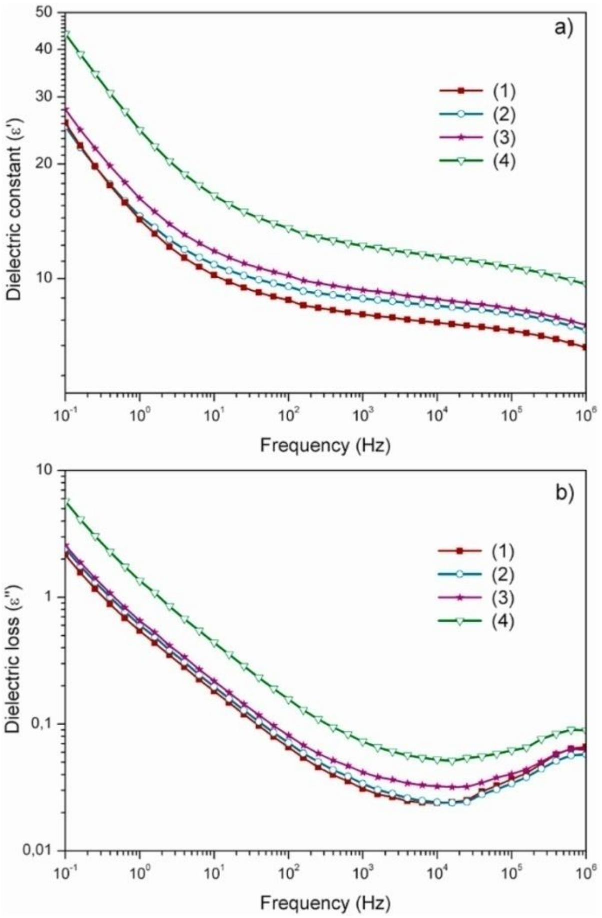

Fig.5 (a): Graph between Dielectric constant and frequency (b) dielectric loss v/s frequency for the pure co-polymer

However, the polymer matrix contributes maximum to the powerful dielectric permittivity because of the lots better dielectric permittivity of the perovskite particles. Typically, a higher filler concentration is required to increase the permeability of the composite. For this reason, it is believed that the increase in the effective dielectric constant of the composite is due to the synergistic effects of the high dielectric constant of the particles and the reduced mobility of the chains after their introduction into the copolymer matrix. Dielectric losses vs. Frequency curves of the Poly(vinylidene-fluoride-hexafluoropropylene) co-polymer and the PVDF-HFP composites obtained at room temperature$^{18-19}$.

DIELECTRIC PRODUCTION OF P(VDF-HFP) FILMS

The dielectric constant (E') of the Poly(vinylidene fluoride-hexafluoropropylene) movies crystallized from DMF and NMP are the take a look at frequency range, and the (E') of the Poly(vinylidene fluoridene-hexafluoropropylene) have a protracted molecular chain of polar polymer growing from the crystalline place to amorphous place. When we deliver a massive dipole second then we have an excessive dielectric regular. It is accurate due to the fact with side the β section 4 movies are represented through the crystal form. Then the dielectric regular distinction among them is unreadable. Although, whilst the frequency growth then the attention of the molecular dipole second is decreased. We can say that frequency is inversely non-public to the dielectric regular. The dielectric lack of the pattern is coincident with side the take-a-look-at-the band. Finally, the primary end is that solvent has much less impact on the dielectric spectrum of Poly(vinylidene fluoride-hexafluoropropylene) movies.20

THE EFFECTS OF THERMAL, MECHANICAL AND STRUCTURAL PROPERTIES OF (PVDF-HFP) DIELECTRIC POLYMER

THERMAL PROPERTIES

The properties of any material film turn on the temperature of the dielectric polymer, here the glass temperature is Tg, the melting temperature is Tm, and the melting entropy is ΔH. Melting entropy and crystallization temperature represent a cooling property but the glass temperature represents a reheating property and Poly vinylidene fluoride-hexafluoropropylene) is an amorphous polymer that has a thin flame, the crystallography was approximately 29% but when we add any dielectric polymer then its crystallite will decrease and now it will be approximately 22%. Thermo grams tell that weight loss in temperature between ranges of approximately 410ºC to 490ºC. The pure Poly vinylidene fluoride-hexafluoropropylene) is imputing the humiliation of the dielectric polymer backbone. Here, mainly three major weight loss parts are detected. The first is around 105ºC which happens the loss of H2O that makes the hydrogen fluoride bond, the second area range is approximately 110ºc to 325ºC then the complex humiliation process output is decreased in humiliation temperature. The third part range of approximately 330ºC to 570ºC was assigned to the demolition of the polymeric chain by a decrease in temperature. The thermal stability of dielectric polymer electrolyte film increase when we increase the sample dose.15-22

STRUCTURAL PROPERTIES

By the x-ray diffraction setup of the Poly(vinylidene-fluoride-hexafluoropropylene) polymer can be seen that the many-phase crystalline structure in a dielectric polymer was detected. The old publication presented a peak cantered at $2\theta = 30^{o}$, which was assigned due to the β phase then the total addition of the diffraction in any selected peak like (110) and (200) planes. The next peaks cantered at 27, which was assigned the diffraction in the crystalline phase because the deep peak was detected at $2\theta = 42^{o}$c, due to the crystalline surface being noticed by a polarized light optical microscope. The crystal grain size was assigned to the presence of three phases of Poly(vinylidene fluoride-hexafluoropropylene). In the γ phase, large crystal gain sizes are presented[23.]

MECHANICAL PROPERTIES

Mechanical properties of Poly(vinylidene fluoride-hexafluoropropylene) were resolved using a technology. The results show that the Poly(vinylidene-fluoride-hexafluoropropylene) decreases the elastic modulus and hardness of the films. The elasticity of the Poly (vinylidene fluoride-hexafluoropropyleve) films was 1.61 ± 0.01

GPa film. The difference between the samples was defect by the surface hardness. The variation in the loss modulus, storage modulus, and loss factor (tanƨ) with the frequency of modulation that's depth is 5µm for Poly(vinylidene fluoride-hexafluoropropylene) polymer. The value of storage modulation was gained to be higher modulated as compared to loss modules. But when we will add the Poly(vinylidene fluoride-hexafluoropropylene) thin films will decrease in both storage modules and loss modules. The storage modules' thin films decrease for 0.2 GPa When frequency will decrease. But loss modules are independent of frequency. The loss factor constitutes the ratio of storage modules and loss modules, presenting the same thin films with a very less value of Poly (vinylidene fluoride-hexafluoropropylene)[22-25].

DIELECTRIC POLYMER (PVDF-HFP) ELECTROLYTE FILMS WITH ELECTRON BEAM

NON-VOLATILE MEMORIES

This is a type of memory that can store information when we off the computer. RAM is based on bi- stable state that can be shift by an appeal electric field. When we compare the silicon flash memories, the main advantage of flash memories is it takes very low power and long permanence. For practices, binary data uses '0' and '1' for data storage cell. Due to the reason of low cost and good processing dielectric polymers have a normal behavior are good for the next generation. The feedback of the memory device is based upon the behavior of the dielectric material[22-24.]

LINEAR POLYMERS

A linear dielectric polymer is a unique cloth whose polarization expresses a linear dating with the electrical discipline. In linear polymers, the dielectric consistency is invariable with extrude of discipline, frequency, or even temperature. Linear dielectrics with low power loss are gambling dominant roles with side the present-day electric-powered strength device for their large advantages, consisting of the low power loss, excessive breakdown strength, excessive impedance, a huge running temperature variety, and occasional cost. Currently, biaxial-orientated polypropylene is assumed nevertheless one of the few to be had polymers in capacitors. Nevertheless, increasingly scientists had been now no longer glad about the exceedingly small dielectric consistent and occasional discharging power density of Biaxially oriented isotactic polypropylene (BOPP). Spontaneously, PVDF-primarily based dielectrics have attracted tremendous interest for their exceedingly large dielectric consistency than that of Biaxially oriented isotactic polypropylene (BOPP. Moreover, PVDF-primarily based dielectrics own excessive electric powered breakdown electric powered discipline. Therefore, those homo polymers are predicted to be the high-quality preference of capacitors coordinate substances with excessive dielectric reaction coupled with electric-powered discipline impartial properties[25-27].

However, due to the sturdy C–F bond, the maximum of the PVDF-primarily based homo polymers display the characters of the non-linear dielectric consistent with the frequency or temperature until its miles fabricated. Recently, it becomes found, at ambient temperature, Poly tetrafluoroethylene and ammonium perfluorooctanoate P(TFE–HFP)) movies, skinny movies confirmed linear dielectric behavior as Biaxially oriented isolactic polypropylene (BOPP) through hot-urgent observed through uniaxially stretching. The insertion of (HFP) monomer reasons a lower T m so that P (TFE–HFP) may also soften at excessive temperatures and is without difficulty processing. The exceedingly low content material of HFP monomer enables keeping the bulk of the crystalline segment in P

(TFE–HFP) with an exceedingly excessive diploma of crystalline of 61.6%. That is anticipated from the differential scanning calorimetric.

CONCLUSION

Polyvinylidene fluoride-hexafluoropropylene composites are filled by two types of fillers nano wires has been fabricated by in situ dispersive polymerizations. The results of “XRD, SEM, and TEM” justified the incorporation of the Polyvinylidene fluoride-hexafluoropropylene matrix. With increasing content, enhancements of the dielectric constant are found in both types of composites.

In conclusion, we have fabricated a high-e polymer-based composite with low inorganic content (≤10 vol%), with an outstanding insulation with affecting its mechanical properties. The proposed work may find applications in the manufacturing of printed circuit boards (PCBs).

REFERENCES

Fujia Chen, Yuetao Zhao, Yujiu Zhou, Jianhua Xu, Yajie Yang, Wenyao Yang. "Effect of solvent on the energy storage property of poly(vinylidene fluoride hexafluoropropylene)",Materials Research Express, 2020

Takuya HOSHINA. "Size effect of barium titanate: fine particles and ceramics" , Journal of the Ceramic Society of Japan, 2013

Prateek, Vijay Kumar Thakur, Raju Kumar Gupta. "Recent Progress on Ferroelectric Polymer-Based Nanocomposites for High Energy Density Capacitors: Synthesis, Dielectric Properties, and Future Aspects" , Chemical Reviews, 2016

J. Yang, J. Zhang, C. Y. Liang, M. Wang, P. F. Zhao, M. M. Liu, J. W. Liu and R. C. Che, ACS Appl. Mater. Interfaces, 2013, 5,7146–7151.

YÄ±lmaz, Onur, Aurica P. Chiriac, Catalina Natalia Cheaburu, Loredana E. Nita, GÃ¼rbÃ¼z GÃ¼lÃ¼mser, Donatella Duraccio, SossioCimmino, and Cornelia Vasile. "Nanocomposites Based on Montmorillonite/Acrylic Copolymer forAqueous Coating of Soft Surfaces" , Solid State Phenomena, 2009.

W. Z. Ma, J. Zhang, S. J. Chen and X. L. Wang, Appl. Surf. Sci., 2008, 254, 5635–5642.

Chongyang Yang, Minqiang Sun, Xi Wang, Gengchao Wang. "A Novel Flexible Supercapacitor Based on Cross-Linked PVDFHFP Porous Organogel Electrolyte and Carbon Nanotube Paper@π-Conjugated Polymer Film Electrodes" , ACS Sustainable Chemistry & Engineering, 2015

L. Krishna Bharat, G. Seeta Rama Raju, Jae Su Yu. "Red and green colors emitting sphericalshaped calcium molybdate nanophosphors for enhanced latent fingerprint detection" , Scientific Reports, 2017

Huiying Chu, Chao Fu, Jingjing Xu, Weiyan Li, Jing Qian, Wei Nie, Xianghai Ran. "Carbondoped inorganic nanoassemblies as fillers to tailor the dielectric and energy storage properties in polymer-based nanocomposites" , Materials & Design, 2020

Luo, Hang, Dou Zhang, Chao Jiang, Xi Yuan, Chao Chen, and Kechao Zhou. "Improved Dielectric Properties and Energy Storage Density of P(VDF-HFP) Nanocomposite with Hydantoin Epoxy Resin Coated BaTiO3" , ACS Applied Materials & Interfaces

Sheng Peng. "Synthesis and Characterization of Monodisperse Hollow Fe3O4

N. Bao, L. Shen, G. Srinivasan, K. Yanagisawa and A. Gupta, J. Phys. Chem. C, 2008, 112,8634–8642.

F. Liu, R. M. Huo, X. Y. Huang, Q. Q. Lei and P. K. Jiang, IEEE

Trans. Dielectr. Electr. Insul., 2014, 21, 1446–1454.

T. W. Odom, J.-L. Huang, P. Kim and C. M. Lieber, J. Phys. Chem. B, 2000, 104, 2794–2809.

M. Bockrath, W. Liang, D. Bozovic, J. H. Hafner, C. M. Lieber, M. Tinkham and H. Park, Science,2001,291,283–285.

Onimisi MY, Ikyumbur TJ. Comparative analysis of dielectric constant and loss factor of pure Butan-1-ol and ethanol. American Journal of Condensed Mtter Physics. 2015a;5(3).

S. Wada, T. Hoshina, H. Yasuno, S.-M. Nam, H. Kakemoto, T Tsurumi and M. Yashima, J. KoreanPhys.Soc.,46,303¬307(2005).

T. Hoshina, H. Kakemoto, T. Tsurumi, S. Wada, M. Yashima K. Kato and M. Takata, Key Eng. Mater.,301,239¬242(2006).

H. Hayashi, T. Noguchi, N. M. Islam, Y. Hakuta, Y. Imai and N. Ueno, J. Cryst. Growth, 2010, 312,1968–1972.

M. Zgonik, P. Bernasconi, M. Duelli, R. Schlesser, P. Gunter, M. H.Garrett, D. Rytz, Y. Zhu and X. Wu: Phys. Rev. B 50 (1994) 5941.

K. Terabe, M. Nakamura, S. Takekawa, K. Kitamura, S. Higuchi, Y. Gotoh and Y. Cho, Appl. Phys.Lett.,2003,82,433–435.

Laurent, M., Vuillermoz, P.L., “Conductivitéthermique des solides”, Techniquesdel’ingénieur, Constantesphysico-chimiques, K 420, 1993, pp. 1–30

Gou, J., Dai, Y., Li, S., & Tao, W. (2015). International Journal of Heat and Mass Transfer Numerical study of effective thermal conductivities of plain woven composites by unit cells of differentsizes.HEATANDMASSTRANSFER, 829840.doi:10.1016/j.ijheatmasstransfer.2015

Zain-ul-abdein, M., Raza, K., Ahmad, F., &Mabrouki, T. (2015). Numerical investigation of the effect of interfacialthermal resistance upon the thermal conductivity of copper / diamond composites.JMADE,86,248–258.doi:10.1016/j.matdes.2015.07.059

Zhou, Y., Hyuga, H., Kusano, D., Yoshizawa, Y., Ohji, T., &Hirao, K. (2015). Journal of Asian Ceramic Societies Development of high-thermal-conductivity silicon nitride ceramics. Integrative Medicine Research, 3(3), 221–229.doi:10.1016/j.jascer.2015.03.003

Zhu, M.; Huang, X.; Yang, K.; Zhai, X.; Zhang, J.; He, J.; Jiang, P. Energy storage in ferroelectric polymer nanocomposites filled with core-shell structured polymer@BaTiO3 nanoparticles: Understanding the role of polymer shells in the interfacial regions. ACS Appl. Mater. Interfaces 2014, 6, 19644–19654.

Xie, L.; Huang, X.; Yang, K.; Li, S.; Jiang, P. “Grafting to” route to PVDF-HFP-GMA/BaTiO3 nanocomposites with high dielectric constant and high thermal conductivity for energy storage and thermal management applications. J. Mater. Chem. A 2014, 2, 5244–5251.