Flexible Vibrotactile Actuator Based on Soft PVC Gel Embedded Polyaniline/Silicon Dioxide Nanoparticles

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This work was supported in part by the Technology Innovation Program (Development of a film-type transparent/stretchable 3D touch sensor/haptic actuator combined module and advanced UI/UX) funded by the Ministry of Trade, Industry & Energy (MOTIE), South Korea, under Grant 10077367 and in part by the Priority Research Centers Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education under Grant NRF-2018R1A6A1A03025526.

ABSTRACT Nanocomposite hybrid materials made of inorganic nanoparticles and organic polymers are fascinating to design high performance polymeric materials, customized in electronics and transportation sectors. In this concern, a soft and flexible PVC gel embedded with silicon dioxide nanoparticles (SDNs) coated with polyaniline (PANI) has been proposed as a dielectric interface in vibrotactile actuator. Soft PVC gels were achieved by plasticization using acetyltributylcitrate (ATBC), an ecofriendly green plasticizer. The optimization of plasticizer content to PVC was precisely controlled and the ratio was kept constant throughout the experiment. PANI was coated on SDN by using chemical oxidative polymerization technique in order to tune the dielectric/electronic properties and minimize the leakage current. Various quantities of PANI-SDNs were loaded to PVC; the behavior of nanocomposite PVC gels as soft vibrotactile actuators was investigated. All the composite materials were comprehensively investigated using different physico-chemical techniques and haptic performance of the optimized PANI-SDN-0.2 nanocomposite PVC gel was assessed. The following are available online at www.xxx.com/xxx/s1, Figure S1. Pictograph representing PANI-SDN-0.2 nanocomposite PVC gel, (a) a flat PANI-SDN-0.2 nanocomposite PVC gel, (b) demonstrating the flexibility of PANI-SDN-0.2 nanocomposite PVC gel, (c) a wavy-shaped PANI-SDN-0.2 nanocomposite PVC gel for actuator design (d) dimensions of the fabricated wavy-shaped PANI-SDN nanocomposite PVC gels. Figure S2. Illustration to demonstrate the fabrication process of the vibrotactile actuator (a) components of the vibrotactile actuator, (b) lower surface of the top layer, (c) assembled vibrotactile actuator, (d) cross-sectional image of the vibrotactile actuator. Figure S3. Experimental environment demonstrating the measurement of haptic performance of PANI-SDN nanocomposite PVC gels. Description: Instrumentation and Characterization Techniques. Figure S4. EDX spectra of PANI (Scale = 1 µm). Figure S5. EDX spectra of SDNs (Scale = 1 µm). Figure S6. EDX spectra of PANI-SDNs (Scale = 1 µm). Figure S7. EDX spectra of PANI-SDN-0.2 nanocomposite PVC gel (Scale = 1 µm). Figure S8. (a & b) FESEM micrographs of PANI-SDN-0.2 nanocomposite PVC gel with different magnitudes (Scale = 2 µm and 200 nm respectively). Figure S9. Acceleration performance of PANI-SDN-0.01, PANI-SDN-0.05, PANI-SDN-0.1, PANI-SDN-0.3, PANI-SDN-0.4 and PANI-SDN-0.5 nanocomposite PVC gel based actuators.

INDEX TERMS Actuators, nanocomposites, polyaniline, silicon dioxide, vibrotactile haptic devices.

I. INTRODUCTION Composite hybrid materials are formed by the combination of both inorganic and organic components in the bulk and surface structure. The rigidity of the inorganic materials with the flexibility of surface chemistry makes them attractive in designing high performance materials for specific applications [1]–[4]. Among various nanoparticles/nanoarchitectures, silicon dioxide nanoparticles (SDNs) are interesting in the context of electronic device applications [5]–[7]. Hybrid composite nanostructure materials made of SDNs are ideally been explored by imbedding in diverse
electroactive polymers to construct nanocomposite dielectric films for multiple electronic memory circuit components/devices [8]–[10]. The tunable optical, dielectric and electronic properties of SDNs in dielectric matrix predominantly offer a wide range of applications straddling from electronics and optics, to sensors and actuators [11]–[16]. Recently, significant research interest has been focused on surface modified SDNs in designing plasmonic substrates for integrated photonic devices, optical amplifiers and nano/microelectronics devices [17], [18]. In order to tune the dielectric/electronic, optoelectronic, catalytic properties, there has been a tremendous interest in coating organic polymer over inorganic nanoparticles [19]–[21]. Among various researched conducting polymers, polyaniline (PANI) is the foremost technologically promising conducting polymers because of its simple synthesis, low cost, unique redox behavior, and chemical stability, and comparatively high conductivity [22]–[24]. Although several methods are reported for the synthesis of micro/nano sized PANI-coated SDNs, coating of silica nanoparticles with PANI continues to be challenging and a more simple alternative methods are highly desired [25]–[27]. Since SDN possesses acidic surface environment, serve as templates for adsorption of aniline monomers, progressive research has been undertaken to design core–shell nanostructures [28]–[30]. The robust and highly bounded PANI over SDN can be achieved by covering SDN with 3-amino benzoic acid, followed by copolymerizing aniline by chemical oxidative polymerization route leads to highly stable PANI anchored SDN surfaces [31]–[34]. Today, fascinating research findings regarding soft actuators made from elastomeric active materials can find widespread potential implementation in assistive wearable devices [35], [36]. Since the actuator performance was critically depends on mechanical properties and response time, improvement in these parameters is a challenging task for researchers. The practical scientists are interested to design and fabricate a fast-response, stiffness tunable vibrotactile soft actuators [37]–[39]. Because of the slow response time of ionic dielectric electro active polymers (EAPs) in compare to non-ionic dielectric EAPs, several challenges were outcome on non-ionic dielectric EAPs [40]–[42]. Recently, we have developed a soft vibrotactile actuator based on an ePVC gel with SDNs. We used acetyltributylcitrate (ATBC), as an ecofriendly green plasticizer to fabricate the ePVC gel. The proposed actuator rendered a variety of haptic sensations in a wide frequency range [16]. Since, PANI coated hybrid inorganic nanoscale materials shows excellent sensor/actuator performances, we conducted research to dope conducting PANI on SDNs to enhance the performances of vibrotactile actuators by fine tuning of its dielectric properties and mechanical stability. 

Herein we report the fabrication PANI-SDNs nanocomposite PVC gels with various loading of PANI-SDNs to PVC to maximize the actuation performance. Since the low dielectric loss and high dielectric constant is, the key factor to increase the vibrotactile force of the PVC gel-based actuators, tuning of dielectric properties was requisite to improve the haptic behavior of plasticized PVC gel. This was achieved by embedding PANI-SDNs to plasticized PVC gels in different stoichiometric ratios. The designed soft PANI-SDNs nanocomposite PVC gels are particularly attractive for the implementation in wearable electronic equipment systems due to their low cost and ease of fabrication.

II. MATERIALS AND METHODS

A. CHEMICALS USED

Polyvinylchloride (Mw ∼233000), aniline (ACS reagent, ≥99.5%), ammonium persulfate (ACS reagent, ≥98.0%), acetyltributylcitrate (∼98.0%), silicon dioxide (nanopowder, <100 nm particle size), 3-aminobenzoic acid (∼98.0%) were obtained from Sigma-Aldrich (Seoul, South Korea) and used without any further purification. All the other chemicals and solvents are of reagent grade and used as received. HPLC grade water was used throughout the study.

B. SYNTHESIS OF 3-AMINO BENZOIC ACID - DOPED SDNS (3-ABA DOPED SDNS)

Silicon dioxide nanoparticles (SDNs) were covered using 3-amino benzoic acid as follows. In a 500 mL round bottom flask, 3-amino benzoic acid (1.5 g) was dissolved by the addition of 50 mg of sodium hydroxide in 100 mL of ethanol and 200 µL of HPLC grade water. The clear solution of 3-amino benzoic acid was obtained after heating the reaction mixture at 80 °C. The reaction mixture was sonicated for 2 h, after the addition of 1.5 g of SDNs to the aforementioned solution. After sonication, the reaction mixture was stirred continuously at 80 °C for about 24 h. Finally, the obtained 3-amino benzoic acid-doped SDNs were collected using centrifugation, washed thoroughly with hot ethanol for several times, and dried in a hot air oven at 60 °C for 24 h (See Figure 1. Step 1, for schematic illustration).

FIGURE 1. Schematic illustration of PANI-SDNs formation.
C. PREPARATION OF POLY(ANILINE-CO-3-AMINO BENZOIC ACID) - COVERED SDNS (PANI-SDNS)

Poly(aniline-co-3-amino benzoic acid) - covered SDNs (PANI-SDNs) was synthesized by copolymerizing aniline and 3-amino benzoic acid - doped SDNs in a 1:2 ratio respectively [31]. Typically, in a 250 mL round bottom flask, 2.0 g of 3-amino benzoic acid - doped SDNs were dispersed in 100 mL of 0.5 M HCl solution. Subsequently, added 1.0 g of aniline and stirred well to get a homogeneous mixture. The reaction mixture was cooled to 5 °C. An ice-cold solution of ammonium persulfate (5.0 g in 10 mL) was added dropwise to the above homogeneous reaction mixture. After 45 min of complete addition of ammonium persulfate solution, the reaction mass changed its colour to a dark green. The stirring was continued for about 24 h at room temperature. After completion of reaction, the obtained product was collected by centrifugation at 10000 rpm, washed thoroughly with HPLC grade water, and dried in a vacuum oven at 60 °C for about 24 h (See Figure 1. Step 2, for schematic illustration). Similar conditions were adopted to synthesize PANI for comparative studies [32], [34].

D. PREPARATION OF PANI-SDNS NANOCOMPOSITE PVC GELS

Soft and flexible polyvinylchloride (PVC) gels doped with PANI-SDNs were prepared at room temperature by simple solution casting method. The weight ratio of acetyltributyl-citrate (ATBC) to PVC was optimized and kept constant throughout the experiments. Typically, PVC (1 g) was dissolved in 20 mL tetrahydrofuran (THF) at ambient temperature (21 − 22 °C), a known amount PANI-SDNs were loaded into the polymer solutions separately, followed by the addition of 5 mL of ATBC plasticizer (For PANI-SDN-0.01, 10 mg of PANI-SDNs were dispersed in THF (20 mL) containing 1 g of PVC). The nanocomposite suspension solution was sonicated for 10 h for uniform distribution of PANI-SDNs throughout PVC matrix. The homogeneous nanocomposite suspension was cast onto a glass plate. The nanocomposite gels were allowed to dry for three days and were subsequently peeled off. The stoichiometric mass ratio of PANI-SDNs with respect to PVC was varied as 0.01, 0.05, 0.1, 0.2, 0.3, 0.4, and 0.5, and the resulting nanocomposite gels were labelled as PANI-SDN-0.01, PANI-SDN-0.05, PANI-SDN-0.1, PANI-SDN-0.2, PANI-SDN-0.3, PANI-SDN-0.4 and PANI-SDN-0.5, respectively.

E. ACTUATOR DESIGN AND FABRICATION

The framework for vibrotactile actuator design was same as previously developed from our interaction lab [16], [43]. In detail, the structural components for actuator was composed of three main components: (1) top layer, (2) a wave shaped PANI-SDN nanocomposite PVC gel layer, and (3) bottom layer. The detailed fabrication process of an actuator was described in our previous literature [16]. The dimension of the actuator was 25 mm (L) x 25 mm (W) x 0.5 mm (H). The wave-shaped PANI-SDN nanocomposite PVC gel was sandwiched between an actuation part of the top layer and the bottom layer. The gold electrode was applied to the both top and bottom layer. In addition, the gold electrode was also concealed by the upper part of the bottom layer. The designed vibrotactile actuator composed of PANI-SDN-0.2 nanocomposite PVC film was presented in Figure 2 (For detailed fabrication process of the vibrotactile actuator, see Figure S2, supplementary information). According to Hooke’s law of elasticity, for relatively small deformations of an object, the displacement of the deformation is directly proportional to the deforming force. Thus, the fabrication of wave-shaped PANI-SDN nanocomposite gels were prepared, in order to to maximize the displacement in our small and thin designed actuators. The homogeneous nanocomposite suspension was poured into a wave-shape carved Teflon dishes. Later, the wave-shaped nanocomposite gels with 0.4 mm of thickness (with distance between two ridges = 2 mm) was removed from the Teflon dish after 72 h (for snapshots of nanocomposite gels, see Figure S1 in supplementary information).

III. RESULTS AND DISCUSSION

Thermogravimetric measurement result of PANI, SDNs and PANI-SDN was presented in Figure 3. From the TGA graph, we can notice that SDNs showed higher thermal stability. The SDNs showed the weight loss of 7.8 % below 150 °C, which is endorsed to the physisorbed water molecules on the surface of SDNs. With further increase in temperature, SDNs experiences almost negligible degradation up to 800 °C. Only 3.6 %

FIGURE 2. Pictograph showing designed vibrotactile actuator made of PANI-SDN-0.2 nanocomposite gel.

FIGURE 3. TG plot of PANI, SDN and PANI-SDN under N₂ atmosphere at a heating rate of 10 °C/min.
of observed weight loss of SDN in the temperature range 150–800 °C, signpost the thermal stability of SDNs. However, PANI showed two-stage degradation. Initial degradation of PANI was observed in the temperature range 110–225 °C. The maximum weight loss was observed in the second stage degradation of PANI in the temperature range 300–800 °C and the residual mass was found to be 26.2 %. The TG pattern of PANI-SDN was in proximity with the pattern of SDNs and PANI. Initially the degradation pattern followed the pattern of PANI weight loss of 15.2 % over the temperature range 150–350 °C. The final step degradation was observed in the temperature range 350–800 °C, where 39.5 % weight loss is encountered with residual mass of about 60.4 %. Since PANI and SDNs coated PANI are hygroscopic, the observed TG degradation pattern showed weight loss below 100–150 °C due to physically adsorbed water and solvents molecules.

Thermogravimetric measurement was also performed for PVC and PANI-SDN-0.2 nanocomposite PVC gels and data were presented in the Figure 4. From the TGA plot, it is clear that PVC suffers degradation in three steps, whereas two main degradation steps were observed in case of PANI-SDN-0.2 nanocomposite PVC gels. Initial weight loss of 8 % for PVC at around 90–250 °C was attributed to the adsorbed solvent molecules and moisture. The dehydrochlorination in the PVC chains, leading to the formation of long sequences of polyenes was observed in the temperature range 250–370 °C, with 55 % weight loss. In the temperature range of 370–480 °C, degradation of conjugated double bonds resulting from dehydrochlorination of PVC chains was observed. However, PANI-SDN-0.2 nanocomposite PVC gels showed slightly reduced thermal stability because of plasticization using ATBC. The initial weight loss was observed in 150–350 °C temperature range with 85 % weight loss. Because of increased free volume induced by ATBC plasticizer allows the better diffusion of formed hydrochloric acid (HCl) gas during dehydrochlorination of PVC. The second major degradation was observed in temperature range of 370–480 °C temperature with 10 % weight loss [44], [45].

The X-ray diffraction (XRD) pattern of PVC, PANI, SDN, PANI-SDN, PANI-SDN-0.2 showed in Figure 5. The diffractogram of PVC showed characteristic amorphous pattern and major diffraction peaks are observed at 17.5° and 24.5°. The diffractogram of PANI showed peaks at 15.5°, 20.5° and 26.5°, these peaks are corresponding to typical emeraldine salt (ES) phase of PANI’s (011), (020) and (200) planes respectively. The peaks with wide 2θ ranges of SDN signifies its amorphous nature. In case of PANI-SDN, since the diffractogram pattern for PANI is merged with SDN pattern, the 2θ of PANI cannot be easily distinguished in PANI-SDN. The wide 2θ range in PANI-SDN dominates by signposting the amorphous nature. Furthermore, the diffractogram of PANI-SDN-0.2 also not give more information since the peaks of PVC are merged. Moreover, we can observe the shift in the 2θ slightly towards lower angle than SDN and PANI-SDN, also some pattern of PVC is reciprocated which signifies the distribution of PANI-SDN in PVC matrix.

Field emission scanning electron microscopy (FESEM) was performed to analyze the size, shape and texture of the prepared PANI, PANI-SDN and PANI-SDN nanocomposite PVC film (PANI-SDN-0.2). Figure 4 shows the FESEM micrographs for PANI, SDN, PANI-SDN and PANI-SDN-0.2 nanocomposite gel. From the Figure 6a, we can notice the nano PANI particles with variable distorted oval shape and sizes are in the range between 70–150 nm. The SDNs are roughly spherical and sizes are in 50–100 nm (see Figure 6b). The represented micrograph of nanocomposite PANI-SDN in Figure 6c showed roughly spherical SDNs covered with PANI, and sizes of the particles are in the range 110–200 nm.

FIGURE 4. TG plot of PVC and PANI-SDN-0.2 nanocomposite PVC gels under N₂ atmosphere at a heating rate of 10 °C/min.

FIGURE 5. XRD diffractogram of PVC, PANI, SDN, PANI-SDN, PANI-SDN-0.2 nanocomposite PVC gel.
The uniform distribution of PANI-SDN nanocomposites in PVC matrix was observed in the micrograph of PANI-SDN-0.2 nanocomposite PVC gel and presented in Figure 6d. Energy-dispersive X-ray analysis (EDXA), was performed for all the composites and presented in Figures S4, S5, S6 and S7 (see supplementary information). The figures shows the typical absorption pattern for carbon, nitrogen, oxygen, silicon, and chlorine atoms. In addition, FESEM image of evenly distributed PANI-SDNs in PVC matrix can be observed in Figure S8 (see supplementary information) with 2 µm and 200 nm magnifications.

The electrical, dielectric and mechanical properties of PANI-SDNs place an important role in deciding the haptic performances of the fabricated vibrotactile actuators based on PANI-SDN nanocomposite PVC gels. It is notice that, all the prepared dumbbell-shape composite gels were strained by 250 percent at ambient temperature. Figure 7 shows the mechanical properties of PANI-SDN nanocomposite PVC gel samples. The stiffness of the gels are directly proportional to the content of PANI-SDN in PVC matrix. Maintaining the stiffness of the material is most important parameter especially in designing PVC gel based vibrotactile actuators [16], [39], [43]. In the absence of applied voltage, the elastic restoring force of the prepared PANI-SDNs nanocomposite PVC gel actuator will return to its original state. Therefore, the stiffness of the material decides the vibrational force of the actuators. By maintaining the constant plasticizer (ATBC) content, and varying the PANI-SDNs quantity, an optimized PANI-SDN-0.2 nanocomposite PVC gel was attained. The optimized gel operates courteously without deformation under the applied voltage.

Since the dielectric properties are strongly depends on the domain structure and electric-field induced deformation of the gels [16], [39], [43], dielectric performances of PANI-SDN loaded PVC gels were performed and results were presented in Figures 8. From Figure 8a, it is clearly observed that the dielectric constants of the PANI-SDN nanocomposite PVC gels were found in the range of 10–15 at higher frequencies (1000 Hz to 100,000 Hz). Dielectric constant of all the gels were steadily decreased until 100 Hz. Interestingly, dielectric constants of all the gel samples are increased with an increasing amount of PANI-SDN. The dielectric loss results were shown in Figure 8b. As per the plot, the dielectric loss of the PANI-SDN nanocomposite PVC gels with minimum loading (0.01 g) of PANI-SDNs suffers steep decrease when compared with the values of maximum loading (0.5 g) of PANI-SDNs. The dielectric losses of all the gels are well below the value -50 after 100 Hz. The optimum (0.2 g) loading of PANI-SDNs to PVC
constitutes the tuning of dielectric properties which intern decides the performance of designed vibrotactile actuator.

The leakage current measurements of PANI-SDN nanocomposite PVC gels as a function of PANI-SDN content was investigated for each flat, rectangular shape gel samples (0.2 mm thickness) were sandwiched between two parallel electrode plates, with dimensions of 10 mm x 10 mm (For detailed instrumentation and characterization techniques, see description section of supplementary information). The results of leakage current measurements were presented in Figure 9. From Figure 9a, we can notice the each leakage current variation for all the PANI-SDN nanocomposite PVC gels. The maximum measured leakage current for bare SDNs doped ePVC gels from our previous experiments are 11.2 $\mu$A for minimal (0.01 g) loading of bare SDNs and 1.5 $\mu$A for high (0.5 g) loading of SDNs to ePVC [16]. However, the leakage current steadily increased in our case, with increase of PANI-SDN to PVC. Surprisingly, the leakage current of 1.15 $\mu$A for maximum loading (0.5 g) of PANI-SDN and 0.025 $\mu$A for minimum loading (0.01 g) of PANI-SDN (see Figure 9b) was noticed. In our case, the observed values of leakage current are too smaller compared to our previous results [16], which signposts that the developed vibrotactile actuator successfully utilize the electric power for the actuation of PANI-SDN nanocomposite PVC gels and also suggest the high durability of the actuator performances. The material properties such as dielectric constant, dielectric loss, Young’s modulus and maximum leakage current values of respective PANI-SDN nanocomposite PVC gels were summarized in Table 1.

| Gel code   | Dielectric constant | Dielectric loss | Young’s modulus (kPa) | Maximum leakage current ($\mu$A) |
|------------|---------------------|----------------|----------------------|---------------------------------|
| PANI-SDN-0.01 | 10.33               | -930.30        | 706.1                | 0.036                           |
| PANI-SDN-0.05 | 11.81               | -830.81        | 711.8                | 0.048                           |
| PANI-SDN-0.1  | 15.36               | -294.03        | 791.6                | 0.066                           |
| PANI-SDN-0.2  | 26.78               | -224.45        | 828.2                | 0.095                           |
| PANI-SDN-0.3  | 42.61               | -195.52        | 862.0                | 0.177                           |
| PANI-SDN-0.4  | 50.97               | -182.39        | 911.6                | 0.275                           |
| PANI-SDN-0.5  | 65.26               | -154.42        | 917.5                | 1.156                           |

To find the best PANI-SDN nanocomposite PVC gel, suitable for soft vibrotactile actuator, we have done a simple experiment using several PANI-SDN nanocomposite PVC gel based actuators. The experiments are conducted with the function generator (Proteck 9305, Proteck, South Korea), a high voltage amplifier (Trek 10/40A-HS, Trek, New York, NY, USA), and an accelerometer (Charge Accelerometer type 4393, Brü el & Kjær, Denmark). The 100 g mass was attached on the PANI-SDN nanocomposite PVC gel based actuator. To compare the proposed actuators, we used input voltage as 1 kV and 130 Hz (resonant frequency) with sinusoidal wave. The PANI-SDN-0.2 nanocomposite PVC gel has showed highest acceleration than all the other nanocomposite gels. Thus, we selected the PANI-SDN-0.2 nanocomposite PVC gel as a suitable gel for soft vibrotactile actuator. Figure 10 shows the acceleration of the PANI-SDN-0.2 nanocomposite PVC gel based actuator as function of the frequency (input voltage is 1 kV).

The maximum value of the proposed actuator is 0.73 g ($g = 9.8 \text{ m/s}^2$) at 130 Hz. With increasing PANI-SDN
content to PVC, decrease in the vibrational acceleration was observed beyond 0.2 g of PANI-SDN. The similar trend was also observed in our previous studies, where the vibrational acceleration decreased proportionally with the increase in the amount of SDN to PVC [16]. Which can be explained by the collective tuning of dielectric and mechanical properties, which decides the performances of the gels. To check the durability of PANI-SDN-0.2 gels, the gels were kept in a closed glass container at ambient conditions for about 300 days. The reproducibility of acceleration performance was measured after 300 days. Figure 11 demonstrates the durability of the PANI-SDN-0.2 nanocomposite PVC gel. From the plot, no noticeable reduce in the actuation performance was observed even under three days of operation. The obtained maximum acceleration values for respective PANI-SDN nanocomposite PVC gels at corresponding resonance frequencies were summarized in Table 2 (For plot of acceleration performance results of PANI-SDN nanocomposite PVC gels, see Figure S9 in supplementary information).

**TABLE 2.** Acceleration performances of PANI-SDN nanocomposite PVC gels.

| Gel code     | Maximum vibration acceleration (g) | Corresponding resonance frequency (Hz) |
|--------------|-----------------------------------|----------------------------------------|
| PANI-SDN-0.01| 0.33                              | 90.0                                   |
| PANI-SDN-0.05| 0.45                              | 110.0                                  |
| PANI-SDN-0.1 | 0.54                              | 120.0                                  |
| PANI-SDN-0.2 | 0.73                              | 130.0                                  |
| PANI-SDN-0.3 | 0.56                              | 140.0                                  |
| PANI-SDN-0.4 | 0.44                              | 150.0                                  |
| PANI-SDN-0.5 | 0.30                              | 160.0                                  |

**IV. CONCLUSION**

This study has demonstrated that, the dielectric PVC matrix embedded variable PANI-SDN content was favourably utilized as an active interface in designing smart vibrotactile actuators. All the prepared hybrid nanocomposites were physico-chemically characterized using different spectroscopic techniques. It has been observed that all the PANI-SDN nanocomposite PVC gels strained about 250 % and the stiffness of the gels are directly proportional to the content of PANI-SDN in PVC matrix. Fine-tuning of dielectric/electronic properties of plasticized PVC gels has been achieved by loading PANI-SDN. Leakage current measurements of the fabricated PANI-SDN nanocomposite PVC gels are in the range 0.025 µA to 1.2 µA, which signifies that the developed vibrotactile actuators can successfully utilize the applied electric power with minimal power dissipation. The control over the exponential increase in the dielectric losses indicates long durability and high performance of the proposed actuators. The haptic performances of optimized PANI-SDN-0.2 nanocomposite PVC gel based actuator showed acceleration of 0.73 g at 130 Hz (input voltage, 1 kV). The proposed vibrotactile actuators can explicitly address in conveying various haptic sensation to the users and stretch its applications in small smart consumer electronic products.

**ACKNOWLEDGMENTS**

The authors would like to thank the Cooperative Equipment Center at KoreaTech for XRD, TGA and FESEM analysis.

**CONFLICTS OF INTEREST**

The authors declare no conflict of interest.

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