Large Area Pressure Sensor for Smart Floor Sensor Applications—An Occupancy Limiting Technology to Combat Social Distancing

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***Abstract*—With the advent of the recent coronavirus pandemic, it has become crucial to maintain social distancing within public spaces. To achieve this, it is important to keep a count of the number of people entering the premises and maintain low occupancy within it. This article presents a very large area pressure sensor based on nickel sulfide deposited on a paper using facile hydrothermal, and sheet to sheet vacuum filtration technique followed by an encapsulation of the sensor using polydimethylsiloxane for smart floor applications. An android application is also developed for the count of the people and the estimated waiting period for the entry.**

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THE FIELD OF flexible electronics has emerged steadily over the last decade. Past research in flexible electronics, specifically that of flexible sensors has majorly focused on small scale/area pressure, temperature, and humidity sensors. Large-area flexible sensors are vital for the future as they have widespread applications in flexible displays, electronic skins, biomedical systems, wearable electronics.[1,2] These sensors can also be used for a variety of security and monitoring applications, such as tracking the number of people entering a certain area when they step on the large-area sensing surface. The current coronavirus pandemic necessitates social distancing within public spaces like supermarkets and offices so as to protect people from catching the infection. There is no doubt that fast identification of a novel virus could significantly contribute to control of an emerging pandemic, but these are expensive and need extra efforts.[3-5] One of the possible solutions to maintain social distancing is to keep a count of the number of people entering a heavily crowded premises and to maintain low occupancy within it. The existing people-counting and occupancy-limiting technologies are either software based and hence prone to some errors, or they utilize cost-heavy hardware which cannot be deployed in every public space.[6,7] Also, Therefore, an urgent need for inexpensive technological solutions to aid people to go about their daily lives of visiting malls, offices, and supermarkets and at the same time one can avoid getting infected.

There has been extensive research on pressure sensors; however, most of the pressure sensors reported are fabricated on a small area with a focus more on healthcare applications that includes artificial electronic skin, human motion monitoring, touchpads, etc.[1,8,9] But for the mentioned application, there is a need to develop a large area and robust pressure sensor that can sense the pressure exerted by a human. Hence there is a need to develop a process wherein large area fabrication is possible and at the same time maintain the cost of the system to be as low as possible. There are different fabrication processes reported for large-area fabrication that include chemical vapor deposition (CVD), hydrothermal, etc.[10] Sheet to sheet processing technique has gained importance for large area deposition and is compatible with most of the conventional process. Vacuum filtration along with sheet to sheet processing for large area deposition would be an interesting process to explore for the fabrication of large-area devices.

Nanoscale materials are found to be superior to their bulk counterparts due to their interesting properties like high surface area-to-volume ratio, high surface sensitivity, and exceptional semiconducting properties.[11] As compared to their 3-D counterparts, 2-D materials offer more flexibility in tuning their electronic properties. Research of 2-D materials gained momentum after the isolation of graphene. Transition metal chalcogenides (TMCs) of the form MX, MX_2, and MX_3 hence provide good alternatives. Besides having exceptional electrical properties, TMCs have high Young's Moduli and breaking strains. Two-dimensional TMCs can therefore be employed in large-area, high-performance flexible devices, and circuits. The most common TMCs studied in literature are MoS_2 and WS_2, however, among the family of sulfides, there has been a growing interest in nickel sulfide (NiS) owing to its thermal catalytic, magnetic, and optical properties. NiS is an interesting material since it exhibits metal-insulator transition by doping or as a function of temperature and/or pressure.[12]

The following report investigates the fabrication and application of a large-area, cellulose paper-based NiS pressure sensor. The hydrothermal synthesis method was chosen for the synthesis of NiS since it requires crystal growth at high temperatures and pressures. Further, sheet to sheet processing using vacuum filtration was utilized for the deposition of NiS on cellulose paper. Moreover, this synthesis method proved to be better as it is a one-step, environment-friendly procedure having operating conditions that are simple to achieve. To demonstrate the application, the fabricated large-area pressure sensor was then integrated with a microcontroller and a dedicated Android application was created to count the number of people entering a crowded premise. The large area smart floor pressure sensor would be deployed at the entrance of the concerned premises. When people enter a mall, office, or

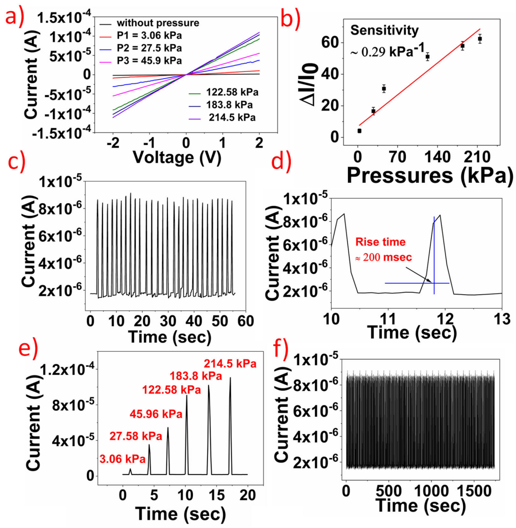

Figure 1. (a) Current–voltage (I–V) characteristics of NiS deposited on paper, showing ohmic behavior of the device. (b) Graph plotted between $\Delta I/I_0$ and applied pressure, sensitivity was found to be ~ 0.29 kPa^{-1}. (c) Temporal response of the sensor for multiple cycles under constant pressure $P = 3.06$ kPa. (d) Graph showing the rise time of the sensor, Rise time ~200 ms. (e) Response of the sensor under various pressures applied. (f) Temporal response of the device under 1000 continues cycles.

supermarket, they would step on the pressure sensor placed on the floor at the entrance. The changes in pressure were mapped as corresponding changes in resistance by the Arduino. The data collected was then transmitted wirelessly to a smartphone application. Every time a person stepped on the sensor, the application would register it as one person entering. People who wish to visit malls or supermarkets can further download this application and check how crowded the area and accordingly plan their travels. The major contribution of the work is the development of a large area pressure sensor and to demonstrate the initial proof of concept prototype to counter the social distancing issue in areas with a high density of people. Further, the overall cost of the entire system is around ~ 6 $ (details are given in supporting information Table S1), which is cost effective as compared to other commercially available options. The successful demonstration of the smart floor sensor opens up new avenues for tackling social distance issue.

RELATED EXISTING WORKS

There are a number of reports on the fabrication of pressure sensors for large area applications. A flexible e-skin pressure sensor, made of carbonized melamine sponge with lycra fabric, was reported by Li *et al.*[13] The fabrication process used was dip-coating and it does not necessarily produce a uniform deposition of the active material. Lin *et al.* reported a large area pressure sensor based on triboeletric effect using Ag nanowires.[14] Yao *et al.* demonstrated the fabrication of a pressure sensor for electronic skin applications based on graphene-wrapped PU sponge.[15] Number of pressures sensors utilizing nanomaterials along with various polymeric substrates such as polydimethylsiloxane (PDMS), PI, etc., have been reported. Although the devices reported show promising results, advanced manufacturing techniques such as photolithography, laser processing, sputtering, etc. are cost ineffective and consume more energy, making them unable to commercialize at large scales. A comparative study of the relative performance of a few reported pressure sensors with the present work is given in Table S2 (SI).

PROPOSED DEVICE DESIGN

In detailed explanation of NiS synthesis is included in the Supporting information (SI). The fabricated NiS/paper with contacts was embedded between two thin PDMS films. Figure S1, SI illustrates the entire synthesis and fabrication process of the NiS/paper device.

CASE STUDY DEVICE ANALYSIS AND DISCUSSIONS

The as-synthesized NiS was confirmed by using several characterization techniques, all the results included in the supporting information (SI), Figure S2. Figure 1(a) displays the current-voltage (I-V) characteristics of as-fabricated NiS/paper and as seen in the graph the device showed ohmic behavior. From the I-V graph, it was observed that the sensor current increases proportionally to the applied pressure on the senor. The linear relationship between the voltage and current shows the steady response of the fabricated NiS/paper sensor to static pressure applied. Sensitivity is one of the figures of merit of the pressure sensor, which is denoted by "S" and determined using the equation $S = (\Delta I/I_0)/(\Delta P)$, where ΔI (final current – initial current) represents the shift in the sensor current after applying a specific pressure and I_0 is the sensor current without any pressure applied. Figure 1(b) displays the graph plotted between $\Delta I/I_0$ and ΔP and the slope of this graph was considered as sensitivity which was found to be approximately $\sim$ 0.29 kPa^{-1}. The sensitivity of the fabricated device is less compared to some of the literature. But the fabrication techniques utilized for such sensors are sophisticated and expensive. Hence it is a cost v/s performance tradeoff. Further, the fabricated device was subjected to a constant pressure of multiple cycles approximately for 60 s and the results are shown in Figure 1(c). From the graph, it was observed that there is a sudden rise in the sensor current immediately after applying external pressure on the sensor. After releasing the pressure, sensor current returns to the initial value. Response time is one of the significant parameters of the pressure sensor, which is defined as the time taken by the sensor current to rise from 10% to 90% of the peak value. The rise time of the fabricated sensor was measured to be approximately $\sim$ 200 ms, as shown in Figure 1(d).

Furthermore, the fabricated sensor was tested under dynamic conditions by applying various pressures and the corresponding temporal response was given in Figure 1(e). As seen in temporal response, the fabricated sensor revealed variations in current levels proportional to the applied pressure. As the applied pressure increases, an increase in the current level was observed, indicating that variations in the pressure values can be clearly differentiated by the fabricated device. To check the reliability, the sensor was testing for 1000 continues cycles. As seen in Figure 1(f), negligible change in the sensor current was observed, suggesting that the high reliability of the sensor and it can be used for multicycle pressure sensing applications. For continuous pressure monitoring, hysteresis is an important parameter. Figure S3a, SI shows the hysteresis graph of the sensor plotted between $\Delta R/R_0$ and pressure applied. Low hysteresis of the fabricated device reveals that the sensing mechanism can be ascribed to tunneling phenomenon instead of rupture/deformation in NiS flowers. To ensure that the external bending does not affect the performance of the sensor, it was put through 500 bending cycles (both tensile and compressive) and the corresponding graph between normalized sensor resistance and bending cycles was drawn as shown in Figure S3b, SI. Negligible deviation of $\pm$2.6% in the sensor response, which reveals the highly robust nature of the sensor.

The change in the fabricated device current due to the applied pressure can be understood by the following reasons. As seen in the high-magnification image (Figure S2c), NiS have a 3-D nanoflower structure having nanorods which looks similar to Christmas-tree nanostructures. These 3-D Christmas-tree nano structures are densely packed and consists of many individual NiS nanorods as seen in high-magnification FESEM image. When external pressure is applied on the sensor, the distance between the nanorods changes significantly, which leads to the change in conductivity of the sensor and it implies the rise in sensor current. Second, individual NiS nanorods are separated by a distance of $\sim$1–3 nm, as revealed from the high-magnification FESEM images, which is a tunneling distance. Because of the external pressure applied, nanoscopic gaps between adjacent nanorods decreases, consequently lower tunneling resistance. The reduction in tunnel resistance increases the tunneling current of the sensor. Thus total sensor current increases due to applied pressure. The fabricated device showed negligible hysteresis [see Figure S3a] and it confirms that the cracks or ruptures in the NiS nanoflowers deposited on cellulose paper are very minimal, which can be ascribed to the remarkable mechanical properties of NiS and the interfacial binding between NiS and cellulose paper substrate post vacuum filtration process. Therefore, instead of the rupture mechanism, the tunneling phenomenon plays a significant role, and thus the accuracy of the pressure sensor output does not deteriorate considerably over time.

Inspired by the high sensitivity and large area of the fabricated NiS/paper-based sensor, it was utilized for lab-based smart floor sensing application. A large area (10 cm $\times$ 4 cm) sensor was fabricated by embedding the NiS/paper between two thin PDMS films and digital image of the

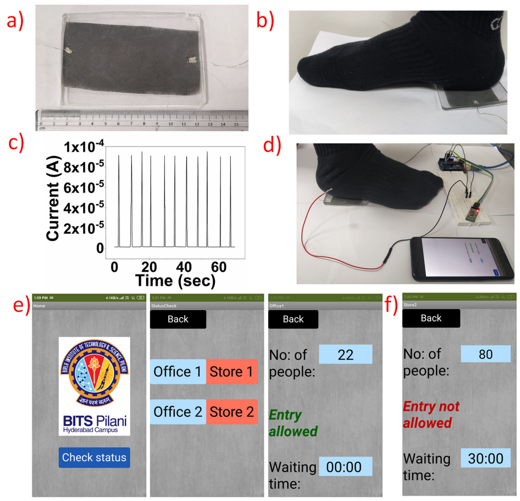

Figure 2 (a) Fabricated NiS/paper-based pressure sensor. (b) and (c) Testing the fabricated device for foot pressure and the corresponding temporal response. (d) Digital image of foot monitoring using smart phone integrated with Arduino board via Bluetooth module. (f) Android application screen showing messages "Entry allowed or not allowed," "number of people," and "waiting time."

device is shown in Figure 2(a). The fabrication process of NiS/paper could be scaled up further for the production large area sensors. To demonstrate the ability of the fabricated pressure sensor, it was tested by keeping the foot of an individual on the sensor for multiple cycles and the corresponding digital image and temporal response are given in Figure 2(b) and 2(c). When the foot was placed on the sensor sudden increase in the sensor current was observed and when the foot was released the sensor current had come back to the initial baseline. By counting the number of peaks/changes in the sensor current/resistance, the number of persons entered can be calculated. An android application was developed to process and monitor the sensor data remotely and the sensor data transmitted to a smart phone using Arduino board via Bluetooth, as shown in Figure 2(d).

The example demonstrated was a lab-based proof of concept testing of a large area pressure sensor. It can be potentially utilized as a smart floor to count the number of people entering the premises which is essential as social distancing has become a "new normal" in today's time. We have the future plan to develop a real time prototype that can be used to check the status of various offices, supermarkets, and malls. It has a counter that registers people entering and leaving premises when they step on the pressure sensor. People can select the place they wish to visit and get information about the number of people present in the place at that time. Some offices may be small in size and may wish to allow only a maximum of fifteen people at a time while some larger supermarkets may allow a hundred shoppers at a time. According to the decided optimal occupancy level of premises, a message shows up on the screen of the application if entry is allowed or not allowed at a given point in time. Furthermore, if entry is not allowed, the application also shows the estimated waiting time period until entry will be allowed again, as depicted in Figure 2(e).

The sensor that was integrated with the HC-05 module must be connected to the mobile app via Bluetooth. For this purpose, the app runs a search for available Bluetooth devices in its surroundings and pairs with the HC-05 module. When a person steps on the large-area sensor, there will be changes in its resistance which get translated as data bytes. These bytes are then sent via Bluetooth to the mobile application. Whenever the app has data incoming via Bluetooth, a counter is set up to count it as one person. When there is no incoming data, the counter remains unchanged. The process will continue, as the number of people entering premises increases, the counter keeps increasing. As long as the number displayed by the counter is below a certain threshold decided by the management of the premises as their optimal occupancy level, a message is shown to the app users signaling that entry is allowed, as shown in Figure 2(e). When the number displayed on the counter becomes equal to the threshold, a different message shows up on the screen signaling users that entry is not allowed Figure 2(f). Further, depending on the average time taken by a person to complete their desired work within the premises, estimated waiting time is decided. This waiting time shows up on the screen [see Figure 2(f)] when the premises saturate to full occupancy. Depending on this waiting time users can decide and plan their travels to the office or supermarket accordingly.

CONCLUSION

In conclusion, the fabricated NiS/paper was utilized as a pressure sensor for smart floor application. The fabricated pressure sensor showed a sensitivity of $\sim 0.29\ kPa^{-1}$ and response time of ~ 200 ms. Furthermore, the future scope of the developed technology could be that of people metering systems for the concept of smart cities and smart mobility wherein authorities can gain insights about how many people are going where and when. This would help in giving feedback to authorities about the changes in people's behavior that would allow them to effectively manage the flow of people or vehicles in the area.

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