Integration of Screen Printed Piezoelectric Sensors for Force Impact Sensing in Smart Multifunctional Glass Applications

Peter Andersson Ersman,* Jerry Eriksson, Darius Jakonis, Sandra Pantzare, Jessica Åhlin, Jan Strandberg, Stefan Sundin, Henrik Toss, Fredrik Ahrentorp, Kaies Daoud, Christian Jonasson, Henrik Svensson, Greger Gregard, Ulf Näslund, and Christer Johansson

Screen printed piezoelectric polyvinylidene fluoride–trifluoro ethylene (PVDF–TrFE)-based sensors laminated between glass panes in the temperature range 80–110 °C are presented. No degradation of the piezoelectric signals is observed for the sensors laminated at 110 °C, despite approaching the Curie temperature of the piezoelectric material. The piezoelectric sensors, here monitoring force impact in smart glass applications, are characterized by using a calibrated impact hammer system and standardized impact situations. Stand-alone piezoelectric sensors and piezoelectric sensors integrated on poly(methyl methacrylate) are also evaluated. The piezoelectric constants obtained from the measurements of the nonintegrated piezoelectric sensors are in good agreement with the literature. The piezoelectric sensor response is measured by using either physical electrical contacts between the piezoelectric sensors and the readout electronics, or wirelessly via both non-contact capacitive coupling and Bluetooth low-energy radio link. The developed sensor concept is finally demonstrated in smart window prototypes, in which integrated piezoelectric sensors are used to detect break-in attempts. Additionally, each prototype includes an electrochromic film to control the light transmittance of the window, a screen printed electrochromic display for status indications and wireless communication with an external server, and a holistic approach of hybrid printed electronic systems targeting smart multifunctional glass applications.

1. Introduction
There is a large interest to monitor forces and strains in complex mechanical material structures (smart materials) and many force/strain sensitive techniques are currently used and further explored, e.g., strain gauges, fiber optics, and capacitive sensors.[1] Another sensor technique that can measure dynamic forces/strains are piezoelectric sensors made of a piezoelectric active material, such as polyvinylidene fluoride (PVDF) or polyvinylidene fluoride–trifluoro ethylene (PVDF–TrFE). By using a variety of material combinations and manufacturing approaches, both piezoelectric films and fiber-based sensors have been demonstrated in many applications where dynamic forces or strains are to be measured, for instance, in situations requiring force impact sensing, stress/strain sensing, acoustics, structural health, as well as in biomedical and energy harvesting applications.[2–19] Piezoelectric sensors for force impact sensing in glass applications...
or other mechanical structures have been studied earlier, and there are even commercial glass break sensors. However, these glass break sensors are applied after completing the window manufacturing, and they are most often large and inconvenient to use.

In this report, we will present results on the manufacturing of tailor made PVDF-TrFE piezoelectric film sensors for impact force sensing in glass applications. The screen printed sensors will be used in a glass break sensor alarm system where the sensors are integrated via glass lamination early in the manufacturing process of the smart multifunctional windows. The thinness of the piezoelectric sensors allows for integration between the glass panes, which has been performed at different temperatures using industrial lamination processes to demonstrate the robustness of the devices. In addition to this, the signal responses from the piezoelectric sensors were analyzed using an effective circuit model. Besides the monitoring of break-in attempts, the light transmittance of the window is controlled by an electrochromic film, a screen printed electrochromic display is used for visualization, and wireless communication is established between the smart window and an external server, i.e., the smart multifunctional glass concept is demonstrated by this hybrid printed electronic system.

2. Piezoelectric Sensor Circuit

When a piezoelectric sensor is subjected to a force or any stresses (strains) due to, for instance, force impact or other mechanical vibrations, an electric charge will be generated, which can be detected as a piezoelectric voltage between the electrodes that is connected to the piezoelectric sensor. Schematically, the piezoelectric sensor can be pictured as a voltage source or a charge source.

A piezoelectric sensor can be seen as a capacitor with a dielectric (permittivity of the piezoelectric material) and a bulk resistance (resistivity of the piezoelectric material). Due to the capacitance (C) and the resistance (R) of the sensor, the effective electric circuit will resemble a high-pass filter with a specific cutoff frequency dependent on C and R \( f_{\text{cutoff}} = 1/(2\pi RC) \). Often the internal resistance of the piezoelectric sensor is very high (\( \Omega \) at low frequencies), but the effective resistance, \( R_{\text{eff}} \), will be the input impedance \( (R_1) \) of the electronics used, e.g., amplifier, oscilloscope, and data acquisition card (DAQ), because \( R \) is coupled in parallel with the input impedance of the electronics. In other cases, \( R_{\text{eff}} \) will be the parallel resistance between the piezoelectric sensor resistance and the input impedance of the electronics. The effective equivalent electric circuit when viewing the piezoelectric sensor as a voltage source can be seen in Figure 1a and can be pictured as an electric high-pass filter.

When measuring the piezoelectric voltages with, e.g., a DAQ-card the frequency content of the impact force versus time response must be considered in relation to the cutoff frequency in order to obtain a proper interpretation of the piezoelectric signal. If the impact force versus time frequency content is higher than the cutoff frequency, most of the piezoelectric input signal is unaffected by the circuit (no phase change), and the piezoelectric voltage versus time is almost equal to the impact force versus time. At other frequencies, the impact force versus time can be calculated from the piezoelectric voltage versus time, according to Equation (1), if the effective resistance and capacitance are known.

\[
V_{\text{out}} + R_{\text{eff}} C \frac{dV_{\text{out}}}{dt} = R_{\text{eff}} C \frac{dV_{\text{in}}}{dt} \tag{1}
\]

When considering sinusoidal forces (that creates sinusoidal input voltage, \( V_{\text{in}} \)) applied to the piezoelectric sensor, the Fourier expression of Equation (1) can be used to derive Equation (2), which gives the characteristic high-pass filter behavior.

\[
V_{\text{out}} = V_{\text{in}} \frac{\sin(\omega R_{\text{eff}} C)}{1 + j\omega R_{\text{eff}} C} \tag{2}
\]

More complicated circuits (by introducing stray capacitances from cables, noncontact capacitive coupling, etc.) can be expressed by using the same methodology. As an example, an effective piezoelectric circuit, in which the resistance of the sensor cannot be neglected, is considered. Additionally, a

Figure 1. a) Effective electric circuit of the piezoelectric sensor (high-pass filter). \( V_{\text{in}} \) (= gtr) is the internal piezoelectric voltage dependent on the piezoelectric constant (g), thickness of the piezoelectric film (t), and the applied stress (\( \sigma = \) force divided by the area where the force is applied, or the product of the strain and the elasticity module of the piezoelectric material). The schematic also shows the capacitance (C) and the resistance (R) of the sensor, and the effective electric circuit when connected to the readout electronics with an input impedance of \( R_1 \). b) Effective electric circuit of the whole piezoelectric sensor circuit where all components are listed. C and R are the capacitance and resistance of the piezoelectric sensor, respectively, \( R_L \) is the loss resistance component of the piezoelectric material (inversely proportional to the imaginary part of the dielectric constant of the piezoelectric material, \( R_L \) should be as high as possible to obtain a low loss piezoelectric sensor), \( C_C \) is the capacitance of the cables connecting the piezoelectric sensor with the readout electronics, \( C_K \) is the coupling capacitance (if the noncontact capacitive coupling mode is used), \( R_1 \) and \( R_2 \) are a voltage divider circuit to decrease the signal (if needed), and \( R_I \) is the input impedance of the readout electronic (DAQ-card or amplifier); thus, the voltage provided by the piezoelectric sensor is measured over \( R_I \).
capacitance in the cables, $C_C$, which connects the piezoelectric sensor to the readout unit (DAQ-card or amplifier), is also considered. This results in that the transfer function in the frequency domain is given by Equation (3)

$$
V_{\text{out}} = V_{\text{in}} \frac{j\omega R_{\text{eff}} C}{1 + j\omega R_{\text{eff}} (C + C_C)}
$$

(3)

$R_{\text{eff}}$ is now the parallel resistance $R_{\text{eff}} = R_L/(R + R_L)$. Thus, the capacitance will damp the piezoelectric signal and the extra resistance from the sensor will only affect the $RC$ time constant of the circuit. In some cases, e.g., when measuring piezoelectric signals with high amplitudes (for instance from high impact forces), the signals must also be actively damped by, for instance, a voltage divider (in the DAQ-card or before the amplifier), and this will affect both the damping and the $RC$ time constant. The full equivalent piezoelectric sensor circuit, when also considering dielectric losses in the dielectric constant of the piezoelectric material together with all other components described, is shown in Figure 1b. The effect of the loss component is further discussed in Section 4, where the capacitance and resistance versus frequency of the piezoelectric sensor are evaluated. The full equivalent circuit, also including a noncontact sensing method with coupling capacitances, $C_K$, is used in all analyses in this report, as shown in Figure 1b. The components in the circuit are all defined in the figure caption. The piezoelectric sensor is viewed as a voltage source also in this case.

3. Experimental Section

3.1. Piezoelectric Sensors

The piezoelectric sensors were manufactured by depositing all layers by using screen printing. Piezotech FC 20 (purchased from Piezotech Arkema) was used as the piezoelectric ink in the screen printing process; it has a PVDF/TrFE molar ratio of 80/20 mol% and a Curie temperature of 136 °C. Ordinary polyethylene terephthalate (PET) film was used as the flexible substrate, and the piezoelectric sensors were screen printed according to a multilayered device architecture (see Figure 2a). The design included two different sensor areas: 2 $\times$ 4 and 8 $\times$ 8 mm. All of the deposited materials were thermally cured. The dry thickness of the printed PVDF–TrFE layer is approximately within the range 4–6 μm. Once the printed layers were thermally cured, the piezoelectric sensors were activated by polarizing the PVDF–TrFE layer. This was achieved at room temperature through electrical poling by applying a voltage between the two electrodes. The applied poling voltage was swept (triangular wave, maximum amplitude of 500 V) to obtain the polarization curve.

![Figure 2. a) Illustration showing the design of the screen printed piezoelectric sensors. The left sensor has an active area of 8 $\times$ 8 mm and the sensor to the right has an active area of 2 $\times$ 4 mm. Features marked in black color represent screen printed silver, i.e., conducting wires and contact pads; this is the first layer that is printed on top of the PET film. The bottom electrode of the sensor is based on screen printed PEDOT:PSS, here marked with light brown color; this layer is printed after the silver features. The piezoelectric PVDF–TrFE layer is subsequently printed on top of the bottom electrode, here marked with a yellow color. Finally, the top electrode is screen printed on top of the PVDF–TrFE layer. The top electrode is also based on PEDOT:PSS, here marked with an orange color. The area of the top electrode is slightly smaller than the bottom electrode, and the top electrode will eventually define the actual piezoelectric sensor area. b) Overview of a laminated glass showing the location of the piezoelectric sensor integration. Sensors denoted “G” are placed between the glass surface and an EVA interlayer, while sensors denoted “M” are placed between the two EVA interlayers. c) Cross-sectional view showing the two different positions, “G” and “M,” of the piezoelectric sensors in the sandwich construction. d,e) A sandwich construction of lamination foils and the piezoelectric sensor device inserted between two glass panes ($= 45$ area) is put in a vacuum bag inside a furnace. The temperature is increased to the softening point of the lamination foils, while air simultaneously is pumped out from the vacuum bag, thereby fully encapsulating the piezoelectric sensor inside the laminated glass.](Image)
3.2. Integration of Piezoelectric Sensors on Acrylic Glass

Piezoelectric sensors, according to the design shown in Figure 2a, were also integrated on rigid (6 mm thick) sheets of acrylic glass (poly(methyl methacrylate) (PMMA)). The purpose of these samples was to investigate the possibility to read the sensor output in a noncontact capacitive coupling mode. The screen printed piezoelectric sensor was attached by an adhesive layer to one side of the PMMA sheet. The silver conductors were prolonged by manual stencil printing of the same silver ink. The stencil was produced by cutting an adhesive layer into the desired pattern, in this case two electrode pads that each had an area of 10 × 10 mm. The stencil printed silver was then thermally cured. The same process was then repeated on the other side of the PMMA sheet. Two electrode pads, each with an area of 10 × 10 mm, were stencil printed opposite to the previously deposited and cured electrode pads, such that the electrode pads were aligned in x-y-direction but separated by the PMMA sheet in the z-direction. The electrode pads deposited on the opposite side of the piezoelectric sensor were also extended by conductors and contact pads at the edge of the PMMA sheet, such that the sensor device, now operating in noncontact capacitive coupling mode, easily could be connected to the readout electronics.

3.3. Integration of Piezoelectric Sensors between Glass Panes

The piezoelectric sensor devices were integrated between glass panes by lamination. 0.76 mm-thick interlayers of ethylene-vinyl acetate (EVA) were used to prepare the samples; two of these interlayers were inserted between the glass panes, with the piezoelectric sensors distributed according to Figure 2b. The positioning of the sensors was chosen to allow response measurements from different areas of the laminated glass. The small squares correspond to piezoelectric sensors with an active area of 2 × 4 mm, while the large squares correspond to piezoelectric sensors with an active area of 8 × 8 mm. The positioning was also chosen to investigate possible differences depending on sensor placement, in the vertical direction, in the sandwich construction of the laminated glass. Sensors denoted “G” in Figure 2b,c are thus located between the glass surface and an EVA interlayer, while the sensors denoted “M” are placed between the two EVA interlayers. In the subsequent lamination process, the prepared samples were placed in a vacuum bag inside a furnace (see Figure 2d,e). The furnace increased the temperature to the softening point of the lamination material, and at the same time air was pumped out from the vacuum bag to eliminate air bubbles. Four different laminated glasses were created by using a respective lamination temperature of 80, 90, 100, and 110 °C.

3.4. Measurement Systems

A calibration system manufactured at Vasasensor AB (Göteborg, Sweden) was used to apply a well-defined and calibrated dynamic force to different stand-alone piezoelectric sensor samples and the piezoelectric sensors integrated between glass panes (see Figure 3a). An impact hammer system with a calibrated force sensor (Model 086D50 from PCB Piezotronics) at the tip is fallen on a sample plate, onto which the piezoelectric sensor samples are placed (pendulum type). The impact hammer calibration signal is 0.23 mV N⁻¹; hence, the voltage versus time measurement of the force sensor results in that the force applied to the samples can be determined. The effective diameter of the hammer, where the force is applied to an even surface, is 30 mm (as measured with a force sensitive film). Upon establishing the electrical coupling between the readout electronics and the piezoelectric sensors, the capacitance is always measured (using a Hameg HM8118 LCR meter, Rohde & Schwarz) in order to verify a good electrical contact to the sensors. The LCR meter was also used to measure the capacitances of the cables connecting the piezoelectric sensor and the readout electronics (DAQ-card or amplifier).

The piezoelectric sensor is either directly coupled, or coupled in noncontact capacitive mode, to an amplifier with adjustable gain (Stanford Research Systems, model SR560, input impedance 100 MΩ). The amplifier transfers the signal to a DAQ-card (National Instruments NI USB-6259) operating at a sampling rate of 50,000 samples s⁻¹ (sufficient sampling rate to provide a detailed view of the piezoelectric signal vs time). A LabVIEW software collects the data from the DAQ-card. In some cases, to improve the signal to noise ratio, a running average filter was used over one sampling period. Most of the measurements are done with differential measurements, i.e., the measured piezoelectric voltage is the difference between the two electrodes connected to the piezoelectric sensor sample. The coaxial cables, connecting the piezoelectric sensor and the amplifier, have a capacitance of 40–250 pF, depending on cable length and how the cables are connected. As the cable capacitance will be added to the capacitance of the piezoelectric sensor, the resulting total capacitance (see Figure 1b) was considered in the analysis to determine the cutoff frequency of the total piezoelectric circuit. As the value of the input impedance is as high as 100 MΩ, together with that the frequency content of the signal response is high compared with the cutoff frequency, all the presented piezoelectric voltages are considered to be measured in open-circuit mode. The generated electric charge from the piezoelectric sensor can be determined by the product of the piezoelectric voltage and the total capacitance (including both the capacitance from the piezoelectric sensor and the cables used to connect the sensors).

The tested glass laminates were mounted rigidly to the hammer system frame with clamps and adhesives between a wooden frame and the hammer system, but each mounted glass laminate could vibrate freely in the center. To avoid any transfer of charges between the hammer tip and the piezoelectric sensor, a thin aluminum film was placed in front of the sample and connected to electrical ground (see Figure 3b). The metallic parts of the hammer were also connected to electrical ground.

A noncontact capacitive (nongalvanic) coupling mode was used in some of the piezoelectric measurements. The method allows for measurements in situations where direct electrical contact with the piezoelectric sensor is disabled. To establish the noncontact capacitive coupling mode, adhesive copper electrodes were mounted on top of the screen printed conducting silver wires that are connected to the piezoelectric sensor, but on the opposite side of the glass. The electric charge generated in the piezoelectric sensor is induced through the glass to the copper electrodes via the electric field, and can therefore be
monitored by connecting the copper electrodes (differentially) to the amplifier.

Wireless sensing of the piezoelectric sensor signal has also been demonstrated by constructing a measuring unit with a Bluetooth low-energy circuit (Texas Instruments, CC2650MODA) including an integrated analog-to-digital converter (ADC/BLE), which allows for real-time transfer of the piezoelectric signal data. The ADC has 12-bit resolution and the supply voltage of the circuit is 4.3 V (single feed), which results in a voltage resolution of ≈1 mV. The sampling rate is 10,000 samples s⁻¹. A MATLAB script is used to collect and display the data from the Bluetooth interface on a laptop computer. The dimensions of the ADC/BLE measurement unit, including the casing, are 35 × 35 × 10 mm.

The responses from piezoelectric sensors integrated in real glass windows were also measured by using a standardized high force impact system (see Figure 4).

4. Results and Discussion

4.1. Piezoelectric Sensors

The piezoelectric sensors were poled, and from the polarization curve (charge density vs the applied voltage to the electrodes of the piezoelectric sensor) a remanence polarization of about 7.1 μC cm⁻² and a coercive electric field of 50 MV m⁻¹ could be determined, which are typical literature values of PVDF–TrFE.[25]

After manufacturing, but before integration between the glass panes, the piezoelectric sensors were tested by first mounting them in the impact hammer system, followed by measurements of the piezoelectric signal and the force versus time upon applying a force. The result of a piezoelectric sensor with the dimensions of 2 × 4 mm is shown in Figure 5. In this case, the sensor is connected directly to the DAQ-card via a coaxial cable, without any damping of the piezoelectric signal.

As can be seen in Figure 5, there is a small disturbance in the piezoelectric signal just before the hammer impacts the sensor. The disturbance is due to an external contribution of charge transfer to the electrodes from the hammer (even when an electrical shield is used between hammer and sample); hence, this is not a signal from the piezoelectric sensor itself. The oscillations in the piezoelectric signal after the impact are due to mechanical vibrations of the sample holder in the hammer system that are detected by the sensor. The piezoelectric signal originating from the actual force impact is the signal step (V_piezo) indicated in Figure 5. The RC time constant for the total circuit is calculated to be ≈30 ms using the input impedance of the DAQ and the total
capacitance (including the capacitances from the piezoelectric sensor and the cables). As this time is much longer than the time of the hammer signal (4 ms), most of the piezoelectric signal will pass the total circuit without any phase change. Hence, $V_{\text{piezo}}$ is the internal peak piezoelectric signal corresponding to the impact force peak signal.

In order to estimate the voltage piezoelectric constant (in this case $g_{33}$), i.e., the applied force and the measured piezoelectric voltage are both in the thickness direction) from the experimental results, the following expression (Equation (4)) of the internal piezoelectric voltage (open circuit voltage) is used, where $i$ is the thickness of the piezoelectric film and $\sigma$ is the applied stress

$$V_{\text{piezo}} = g_{33} \sigma$$

(4)

The peak hammer voltage signal was 0.3 V in the measurement, as shown in Figure 5, which corresponds to a force of 1304 N, or an applied stress of $\sigma = 1.84 \text{ MPa}$ (assuming an even distribution over the hammer area having a diameter of 30 mm). The capacitance of the piezoelectric sensor and the cable is 216 and 105 pF, respectively, which will give a signal damping of 0.67. A piezoelectric signal ($V_{\text{piezo}}$) of 1.07 V is provided in Figure 5 (the amplitude indicated by $V_{\text{piezo}}$), and this voltage will instead be 1.6 V when compensating for the damping of the piezoelectric voltage. By measuring the thickness of the piezoelectric material in the sensor (4 μm), the piezoelectric constant $g_{33}$ can be calculated to be $\approx 0.22 \text{ Vm N}^{-1}$ (Equation (4)). The obtained $g_{33}$ value is in good agreement with the data from the supplier of the piezoelectric ink.[23] The charge piezoelectric constant ($d_{33}$) can also be estimated from experimental results; $d_{33}$ is related to the piezoelectric voltage by Equation (5)

$$\frac{Q}{A_{\text{sensor}}} = \frac{CV_{\text{piezo}}}{A_{\text{sensor}}} = d_{33} \sigma$$

(5)

In Equation (5), $Q$ corresponds to the charges created when the force impacts the piezoelectric sensor and $A_{\text{sensor}}$ is the active sensor area. Inserting values into Equation (5) gives a result of $d_{33} = -23 \text{ pC N}^{-1}$. This is also in good agreement with the data from the supplier of the piezoelectric ink.[23]
The frequency-dependent capacitance and the resistance of the piezoelectric sensor can both be determined through impedance measurements. Both these properties were measured for the piezoelectric sensors by using the LCR equipment, for both nonintegrated and integrated piezoelectric sensors. The results of a piezoelectric sensor with the dimensions of \(8 \times 8\) mm, before and after integration between the glass panes, are shown in Figure 6.

The reason for the decreasing capacitance at approximately 10 kHz is explained by the frequency-dependent real component of the dielectric constant of the PVDF–TrFE material, and the decreasing resistance is due to that the PVDF–TrFE material also has a loss component (imaginary part of the dielectric constant, as previously described in the introduction and in conjunction with Figure 1b) that becomes important for higher frequencies. The frequency dependency of the capacitance can also originate from frequency-dependent AC conductivity. In the measurements in this study, the major frequency content of the impact force from the hammer system is up to 200 Hz, which implies that the capacitance can be considered constant with respect to frequency and that the loss component can be ignored \((R_L \gg 1/(\omega C))\). The capacitance values of the integrated piezoelectric sensors are somewhat higher as compared to the nonintegrated sensors. This is due to that the dielectric property of the glass laminate is added to the total measured capacitance of the piezoelectric sensor.

The thickness of the screen printed piezoelectric layer is typically in the range 4–6 μm. Hence, by assuming a piezoelectric layer thickness of 4 μm, the capacitance of the \(8 \times 8\) mm sensor can be calculated by using a permittivity of 1 (vacuum), and by comparing this value with the capacitance value of the nonintegrated piezoelectric sensor (Figure 6a) at lower frequencies, it is possible to determine the permittivity of the PVDF–TrFE layer. This implies a permittivity of \(\approx 11\), which is in good resemblance with the value given by the supplier of the piezoelectric ink (Piezotech Arkema).

4.2. Integrated Piezoelectric Sensors

A force impact directly at the location of a piezoelectric sensor integrated in the middle of a glass laminate, where the lamination was performed at either 80 or 110 °C, can be seen in Figure 7.

As shown in Figure 7, the peak piezoelectric sensor signal is as high as in the 1 V range, even when applying these low impact forces of 600 N, and the piezoelectric signal follows exactly the shape of the force versus time. This is due to that the cutoff frequency of the piezoelectric sensor and/or the electronic circuit is well below the frequency spectra of the force impact, as described previously. From this result it can also be concluded that the glass lamination temperatures used here (80–110 °C) do not affect the piezoelectric response. If the lamination temperature is too high, as compared to the Curie temperature of the piezoelectric material, the piezoelectric sensor can lose its polarization (partially or fully) and thereby the piezoelectric signal will be reduced. The Curie temperature of the PVDF–TrFE piezoelectric material used in the sensors is 136 °C (see Section 3 on the piezoelectric sensors). The results obtained here indicate that the piezoelectric sensor signal shows no signs of reduction of the signal amplitude, even though the highest lamination temperature was 110 °C, which is approaching the Curie temperature of the piezoelectric material.

The noncontact capacitive coupling mode was also tested to sense piezoelectric signals from sensors integrated between the glass panes. The glass laminated at 80 °C is used as an example, and the results of the piezoelectric signal response when using the contactless sensing method are shown in Figure 8a. The piezoelectric sensor is placed in the middle of the glass laminate and the force impact occurs at the location of the sensor. The result in Figure 8a shows that the noncontact piezoelectric signal is about 1/10 of the sensor signals obtained when using the directly coupled measurement mode (Figure 7b). It should also be noted that the piezoelectric signal may be increased.

Figure 6. Capacitance and resistance of a) nonintegrated and b) integrated \(8 \times 8\) mm piezoelectric sensor (capacitance of 1.8 nF at low frequencies) as a function of the frequency of the applied voltage between the sensor electrodes.
by increasing the dimensions of the coupling electrode. However, for electrode dimensions exceeding $12 \times 30$ mm, the piezoelectric signal will not increase due to that the capacitance of the coupling electrode and the capacitance of the piezoelectric sensor are connected in series, and the capacitance of the coupling electrode increases for larger electrode dimensions. The effective capacitance, $C_{\text{eff}}$, is described by Equation (6)

$$C_{\text{eff}} = \frac{C_{\text{piezo}}C_{\text{coupling}}}{C_{\text{piezo}} + C_{\text{coupling}}} \quad (6)$$

The piezoelectric response has also been tested upon applying the force impact from the hammer adjacent to the position of piezoelectric sensors. Here, the force impact was applied in the center of the glass laminate, while the piezoelectric responses were measured by sensors located in the corners and along the edges of the mounted glass laminate. These measurements, presented in Figure 8b, also resulted in a high piezoelectric signal, and it is also possible to observe the effect of mechanical oscillations in the glass after the force impact, as evidenced by the piezoelectric signal oscillations in the graph from 0.11 s and onward. To further elaborate on this, the distance dependence between the force impact position and the position of the piezoelectric sensor has also been investigated. The results indicate that it should be possible to determine the location of the impact force applied to the glass surface, especially if the piezoelectric...
sensors located in the respective corner of the glass are calibrated prior to the measurements of the impact force signals.

The piezoelectric sensors were also connected to the ADC/BLE unit, and the piezoelectric response was measured after force impact on the glass laminate, both by using the piezo-hammer system (Figure 3) as well as by using the standardized high impact glass test system (Figure 4). A glass sample laminated at 100 °C was used in this experiment. The results obtained by using the hammer system are shown in Figure 9.

Figure 9b shows that the piezoelectric response can be detected even when the piezoelectric sensors are placed at the edges of the glass laminate while applying the force impact in the middle of the glass laminate. It is possible also in this case to detect the mechanical oscillations caused by the force impact, as shown by the piezoelectric signal oscillations.

The results obtained by using the standardized high impact glass test system (Figure 4) in combination with the BLE circuit are shown in Figure 10.

The piezoelectric sensor is also sensitive to high-frequency mechanical oscillations. This can be seen for the sample evaluated in Figure 10b, when a sufficiently high force impact was applied to break the glass. This generated a signal pattern with a completely different high-frequency content as compared to when an ordinary force impact was applied without breaking the glass (Figure 10a). This is an important result that simplifies the signal analysis and enables distinction between a low force impact and glass breakage.

4.3. Smart Multifunctional Window Applications

The term smart window is often used in conjunction with a window that has the possibility to change its light transmittance. There are many different technologies to choose from, and electrochromic smart windows are perhaps among the most commonly used alternative.\[27\] The objective here was to develop
and manufacture prototypes of smart multifunctional windows, i.e., windows having multiple electronic functionalities. As a starting point, an autonomous electrochromic smart window was developed by Chromogenics AB. Besides the electrochromic film covering the large area window, the system also includes a rechargeable battery and a solar cell; hence, no external power supply is required. The energy of the battery is sufficient to change the oxidation state of the electrochromic film, and thereby also the transmittance properties of the window, such that the amount of incoming (sun)light allowed to enter the building can be controlled. Besides the energy harvesting property, the solar cell is also used as a sensor to continuously determine a target transmittance value of the electrochromic film.

Such electrochromic smart windows are commercially available, but several other electronic features were added to the demonstrators developed herein. The most important contribution originates from the already described screen printed piezoelectric sensors. Their sensitivity to mechanical vibrations, along with their unique properties of being extremely thin, flexible, robust, almost transparent and possible to integrate via standard glass lamination methods, allowed utilization of them as alarm sensors in a smart window application to detect break-in attempts. To further expand the multifunctionality of the targeted smart windows, a screen printed RISE Display was also laminated between the glass panes.\textsuperscript{[20,31]} The display, which was designed and utilized mainly for demonstration purposes, contains nine electrochromic segments, e.g., alarm indicator, battery indicator, and the transmittance level of the electrochromic film in the smart window (see Movie S1, Supporting Information for the system initialization of the electrochromic display). Wireless communication between the different silicon-based electronic circuits of the system was established through a LoRa network, as demonstrated in Movie S2, Supporting Information. Finally, an application software was also developed to enable demonstration of the system via computer or mobile phone interfaces. An arbitrary number of smart multifunctional windows may be connected into the network, and as each sensor and each window is uniquely identified, the system is able to monitor the exact location of a triggered alarm. The smart multifunctional glass concept is further demonstrated in Figure 11 and in the Movies S3 and S4, Supporting Information.

5. Conclusions

Integration of screen printed piezoelectric sensors between glass panes and robust mounting of the resulting glass laminates in an impact hammer system have been obtained, and the measurements of the PVDF–TrFE (80/20 mol%) piezoelectric sensors give very good results. Any signal interference, e.g., 50 Hz noise, in the piezoelectric sensor signal can be reduced by a differential measurement setup, and/or by performing running average filtering of the signal (over a 50 Hz period, i.e., 0.02 s).

The charge and voltage piezoelectric constants have been estimated from the experimental results, and the values agree well with the literature data of the PVDF–TrFE (80/20 mol%) material. From the measurements, it has also been determined that the lamination temperature used for the integration of
piezoelectric sensors between glass panes does not affect the piezoelectric response, even when using a relatively high lamination temperature of 110 °C.

Two different measurements modes of the piezoelectric signals have also been evaluated. Direct coupling between the sensor and the electronics (DAQ-card and amplifier) and noncontact capacitive coupling both give good and reliable piezoelectric signals, even though lower piezoelectric voltage amplitudes are recorded when using the contactless technique. In case of the noncontact capacitive coupling mode, the capacitance of the piezoelectric sensor can also be used to optimize the design and the dimensions of the receiving electrode.

An ADC/BLE circuit has also been successfully developed, which enables wireless monitoring of the piezoelectric sensors as well as transfer of sensor data.

It is possible to measure a clear piezoelectric response even if the force impact is located up to 12 cm from the piezoelectric sensor; this is mainly due to mechanical vibrations traveling in the glass laminate. This has been verified for piezoelectric sensors placed at the edges as well as in the center of the glass laminates. As the piezoelectric signals are clear, i.e., free from distortions, it should be possible to measure the piezoelectric response for even longer distances between the location of the force impact and the location of the piezoelectric sensor. High piezoelectric signals are also obtained for sensors placed at the edges and the corners of the glass laminates, upon hitting with the impact hammer at the center of the glass laminates. Also, even if the piezoelectric signal is reduced, as compared to a hit directly on top of the sensor, it is still possible to measure the piezoelectric response with the amplifier/DAQ-card as well as with the ADC/BLE circuit.

In addition to this, by analyzing the frequency content of the piezoelectric signal pattern, it is possible to distinguish between breaking glass caused by high force impact and a low force impact without any glass breakage.

The piezoelectric sensors were manufactured by screen printing all layers on top of flexible plastic substrates, which results in a very reliable sensor technology exhibiting high manufacturing yield. The robustness allows for sensor integration between glass panes by the lamination methods used by industrial window manufacturers. Hence, the development activities reported herein have resulted in a robust technology that enables additional electronic functionality for smart window applications, for example, to detect break-in attempts and thereby trigger an alarm, by monitoring the piezoelectric response of the sensors integrated inside the windows.

**Conflict of Interest**

The authors declare no conflict of interest.

**Data Availability Statement**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Keywords**

PEDOT:PSS, piezoelectric sensors, printed electronics, screen printing, smart windows

Received: March 18, 2022
Revised: August 19, 2022
Published online: September 16, 2022

[1] J. O. Templeman, B. B. Sheil, T. Sun, Sens. Actuators A-Phys. 2020, 304, 111772.
[2] C. Tuloupa, W. Harizi, Z. Aboura, Y. Meyer, K. Khellil, R. Lachat, Compos. Struct. 2019, 215, 127.
[3] S. T. Jenq, C. K. Chang, Exp. Mech. 1995, 35, 224.
[4] Y. Q. Fu, J. K. Luo, N. T. Nguyen, A. J. Walton, A. J. Flewitt, X. T. Zu, Y. Li, G. McHale, A. Matthews, E. Iborra, H. Dui, W. I. Milne, Prog. Mater. Sci. 2017, 89, 31.
[5] M. G. González, P. A. Sorichetti, G. D. Santiago, Rev. Sci. Instrum. 2014, 85, 115005.
[6] E. Nilsson, A. Lund, C. Jonasson, C. Johansson, B. Hagström, Sens. Actuators A-Phys. 2013, 201, 477.
[7] W. R. Alia, M. Prasad, Sens. Actuators A-Phys. 2020, 301, 111756.
[8] C. Dagdeviren, P. Joe, O. L. Tuzman, K.-I. Park, K. J. Lee, Y. Shi, Y. Huangh, J. A. Rogers, Extreme Mech. Lett. 2016, 9, 269.
[9] A. G. Bagnall, Phys. Educ. 1989, 24, 365.
[10] C. Y. K. Chee, L. Tong, G. P. Steven, J. Intell. Mater. Syst. Struct. 1998, 9, 3.
[11] A. Khan, Z. Abas, H. S. Kim, I.-K. Oh, Smart Mater. Struct. 2016, 25, 053002.
[12] S. Mishra, L. Unnikrishnan, S. K. Nayak, S. Mohanty, Macromol. Mater. Eng. 2019, 304, 1800463.
[13] W. Nitsche, M. Swoboda, Z. Flugwiss. Weltraumforsch. 1991, 15, 223.
[14] K. Lu, W. Huang, J. Guo, T. Gong, X. Wei, B.-W. Lu, S.-Y. Liu, B. Yu, Nanoscale Res. Lett. 2018, 13, 83.
[15] K. K. Sappati, S. Bhdara, Sensors 2018, 18, 3605.
[16] S. Tuukkanen, S. Rajala, in 2015 IEEE Sensors, IEEE, Busan, 2015.
[17] D. Thaua, K. Kalliitis, F. Domingues Dos Santos, G. Hadzieoannou, J. Mater. Chem. C 2017, 5, 9963.
[18] G. C. Schmidt, P. M. Panicker, X. Qiu, A. J. Benjamin, R. A. Quintana, I. Wils, A. C. Hübeler, Adv. Mater. 2021, 33, 2006437.
[19] M. Aliqué, C. D. Simão, G. Murillo, A. Moya, Adv. Mater. Technol. 2021, 6, 2001020.
[20] Measurement Specialities, Piezo Film Glass-Break Sensors, (adapted from an original article by R. H. Brown, Pennwalt Piezo Film Ltd, 1989), https://docplayer.net/26006970-Piezo-film-glass-break-sensors.html (accessed: March 2022).
[21] Alarmtech, Passive glass break detector, https://alarmtechglobal.com/en/ (accessed: March 2022).
[22] Measurement Specialities, Piezo Film Sensors – Technical Manual, https://www.strainsense.co.uk/wp-content/uploads/2017/08/Piezo_Technical_Manual.pdf (accessed: March 2022).

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

**Acknowledgements**

This project was financially supported by VINNOVA, grant number 2018-01558.
[23] Piezotech, Piezoelectric and Ferroelectric Copolymers Piezotech FC, https://piezotech.arkema.com/en/Products/piezoelectric-copolymers/ (accessed: August 2022).

[24] A. Krozer, C. Johansson, S. Johnsson, B. Wetter, H. Danielsson, G. Perers, WIPO (PCT) WO2004065145A1, 2004.

[25] D. Mao, B. E. Gnade, M. A. Quevedo-Lopez, in Ferroelectrics - Physical Effects (Ed: Mickaël Lallart), IntechOpen, London 2011, Ch. 4.

[26] D. P. Almond, C. R. Bowen, Phys. Rev. Lett. 2004, 92, 157601.

[27] ChromoGenics, The future lies in climate smart and cost effective glass, https://chromogenics.com/ (accessed: March 2022).

[28] Swedish Institute for Standards, Glass in building – Pendulum test – Impact test method and classification for flat glass, https://www.sis.se/en/produkter/glass-and-ceramics-industries/glass/glass-in-building/ssen12600/ (accessed: March 2022).

[29] Swedish Institute for Standards, Windows – Soft and heavy body impact – Test method, safety requirements and classification, https://www.sis.se/en/produkter/construction-materials-and-building/elements-of-buildings/doors-and-windows/ssen13049/ (accessed: March 2022).

[30] RISE Research Institutes of Sweden, Screen printed electrochromic displays, https://www.ri.se/en/what-we-do/expertises/electrochromic-displays, (accessed: March 2022).

[31] P. Andersson Ersman, K. Freitag, J. Kawahara, J. Åhlin, Sci. Rep. 2022, 12, 10959.