Rapid Fabrication Method for Soft Devices Using Off-the-Shelf Conductive and Dielectric Acrylic Elastomers

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Herein, a method to fabricate soft and stretchable devices rapidly by using only commercially available conductive and dielectric elastomer materials with the aid of laser cutting and a layer-by-layer process is presented. The conductive acrylic elastomer is first characterized in terms of its mechanical and electrical characteristics and then applied to various devices, such as soft electrostatic actuators, strain sensors, and stretchable pumps. These devices, which can be fabricated within 15–30 min, exhibit areal actuated strains of up to 163.0 ± 1.0% at 4 kV in the actuators, a highly linear response ($R^2 = 0.995$) for strains of up to 100% with a gauge factor of 0.98 in the sensors, and an output pressure of 0.11 ± 0.08 kPa and flow rate of $20 ± 4 \mu L \text{s}^{-1}$ at 7 kV in the pumps. These performance characteristics are comparable to those reported in the literature. To demonstrate the potential for soft robotic applications, a wearable device is developed (fabrication time of $\approx 15 \text{ min}$), which exhibits multiple functionalities, such as detection of deformations of a human finger, haptic presentation through vibration, and electroadhesion. The results illustrate the high applicability of the presented strategy in soft intelligent systems.

Soft robots and stretchable devices are attracting increasing interest owing to the advantage of their inherent physical compliance, which ensures safe human–machine interaction, adaptability to the surrounding environment, and relatively simple control. Applications of soft matter systems include mobile robots, manipulators, and wearable assistive devices. Soft/stretchable transducers, such as actuators, sensors, and pumps, are the key elements for ensuring the operation of these robotic systems.

Soft devices and transducers are often composed of compliant electrodes and elastomeric substrates (e.g., silicone and acrylic elastomers [AEs]). Researchers have demonstrated stretchable devices in different forms with various electrode materials, such as carbon black and grease, silver inks, liquid metals, carbon nanotubes, graphite, graphene, liquid metals, elastomers, and fabrics. While the devices made of these conductive materials function well, most of them require a time-consuming process involving preparation, patterning, and curing, associated with a dedicated fabrication setup and environment. This can limit the production speed and frequency to change the design for a given specification, especially in prototyping.

One way to facilitate the rapid fabrication of soft transducers is to use off-the-shelf materials, which dispenses with time-consuming processes and enables easy fabrication. Moreover, combining off-the-shelf materials with a layer-by-layer process can greatly speed up the production, as demonstrated by Bartlett et al. They used an acrylic conductive elastomer (3M, eCAP 7850) as the electrodes laminated onto a polydimethylsiloxane (PDMS) substrate, and subsequently, laser-ablated to form a capacitive strain sensor for wearable biomonitoring. However, PDMS requires thermal curing, which can often take several hours to complete. It should be noted that premade PDMS sheets are commercially available (e.g., Wacker Chemie, ELASTOSIL Film 2030), though, to the best of our knowledge, there is no study reported on rapid fabrication using PDMS sheets and electrode materials that are ready-made. Moreover, the fundamental characteristics, such as the mechanical and electrical properties of off-the-shelf electrode materials and their applicability to other stretchable devices, are not very clear.

Here, we present a method to fabricate soft transducers rapidly that uses only off-the-shelf AE materials. We use a commercially available conductive AE (Adhesives Research, ARcare 90366), which is an adhesive film with a thickness of 33 μm, according to the datasheet. The adhesive nature of this material enables it to be laminated on the substrate, which, in our case, is a dielectric AE (3M, VHB 4905, thickness of 0.5 mm). As shown in Figure 1, these materials can be readily and rapidly used in various devices, such as soft electrostatic actuators, strain sensors, and stretchable pumps. These devices can be fabricated within 15–30 min using only laser cutting and layer-by-layer lamination. The dielectric AE, often called VHB, has already exhibited compatibility with a wide variety of soft and stretchable devices (e.g., refs. [37–41]). As mentioned previously, it is less clear how suitable the conductive AE is for the materials in devices of the same type.
To address this issue, we perform a set of experiments to analyze the conductive AE in terms of its mechanical and electrical characteristics. The sample preparation and experimental procedure are detailed in the “Experimental Section.” We first assess the stress–strain behavior. Figure 2a shows the measured stress–strain curve for a strain of up to 190%. In the figure, the dashed line represents the calculated stress–strain curve obtained by fitting of the Yeoh hyperelastic material model,\(^\text{42}\) from which the Young’s modulus of the conductive AE is found to be 0.43 MPa. The elongation at break is observed to be 320 ± 27% (Figure S1, Supporting Information), which shows high stretchability of the material. A relatively large deviation may result from tiny defects along the edge of the sample created by laser cutting. Figure 2b shows the measured stress against multiple cycles of strain (50%, 100%, 150%, and 200%), where the conductive AE exhibits a hysteresis behavior. This result indicates the presence of viscoelasticity, which slows down the sample deformation, as can be observed in the data of the second, third, and fourth cycles, where the stress is zero, even though the strain is higher than 0%. We then investigate the electrical characteristics of the conductive AE for uniaxial strains. Figure 2c shows the applied strain and the resistance change as functions of elapsed time. At 0% strain, the sample has a sheet resistance of 48.5 ± 0.1 kΩ sq⁻¹, which increases with the strain and reaches ≈1200% change for an applied strain of 200%. Similar to the case of the stress–strain test, the resistance change shows a nonlinear response, with a delay, to the applied strain. This nonlinearity often appears in other resistive strain sensors (e.g., ref. [19]), and mainly results from the change in resistivity of the material caused by the deformation. As for the delay observed, it is associated with the material’s viscoelasticity. The data also suggest the presence of creep, whose effect is especially visible between 300 and 500 s. Here, the resistance change takes two bumps, while the applied strain reflexes its value. Finally, we characterize the resistance change in conductive AE under a repeated strain of 50% up to 10⁶ cycles (Figure 2d). The resistive value changes significantly from

![Figure 1](https://www.advancedsciencenews.com)
0 to 10 cycles at first, and then gradually converges to a certain level; upper bound ≈100% and lower bound ≈20% of resistance change. Although this type of resistance–strain behavior can often be observed in other highly stretchable conductive materials (e.g., ref. [24]), the results suggest that the conductive AE may be more suitable for devices that are insusceptible to resistance changes, such as capacitive strain sensors that rely on capacitance changes.[19] The reason behind this phenomenon may be the presence of creep and alignment of the conductive ingredients in the material. Nevertheless, the data indicate robustness of the conductive AE in both mechanical and electrical characteristics for repeated mechanical loading, which is a preferred property for stretchable transducers and soft matter systems that undergo large deformations.

We then fabricate and characterize a set of representative soft/stretchable devices using the conductive AE and dielectric AE. These include 1) dielectric elastomer actuators (DEAs), 2) capacitive strain sensors, and 3) a stretchable pump, as shown in Figure 1. As detailed in the “Experimental Section,” these devices can be fabricated within 15–30 min. As both the conductive and the dielectric AEs are laser-cut along with their protective films, the surface of every layer can be kept clean prior to lamination.

DEAs are a type of electroactive polymers that have been applied to numerous soft robots and devices,[43,44] owing to their excellent actuation characteristics, such as large strokes, fast response, and high electromechanical efficiency.[45,46] A DEA comprises an elastomer membrane sandwiched between two compliant electrodes. When a high voltage is applied (a few kilovolts), electric charges in the electrodes induce electrostatic force (Maxwell stress), resulting in thickness reduction and area expansion. The Maxwell stress \( p \) is expressed as \( p = \varepsilon_0 \varepsilon E^2 \), where \( \varepsilon_0 \) is the permittivity of free space, \( \varepsilon \) is the relative permittivity of the elastomer membrane, and \( E \) is the electric field between the electrodes (\( E = V/d \), \( V \) is the applied voltage and \( d \) is the thickness of the dielectric). We choose to develop a circular DEA shown in Figure 1a–c because it is a typical configuration for characterizing the actuation performance.[47] Here, we assess the areal strain of the electrodes as actuation stroke under DC voltage, and characterize the frequency response by applying AC voltage. As an important parameter that enhances the actuation performance, different radial prestrains in the dielectric AE are used: 100%, 150%, 200%, and 250%. Figure 3a shows the measured areal strain under DC voltage of up to 5 kV. The actuation exhibits a quadratic growth as the Maxwell stress is proportional to square of the electric field (i.e., voltage), as mentioned previously. The data take a maximum value of 163.0 ± 1.0% at 4 kV for the sample with 250% prestrain (corresponding to the electric field of 160 MV m\(^{-1}\)). Above 4 kV, the actuator faces electrical breakdown, resulting from thinning of the dielectric AE caused by the actuation and prestrain, which generates a high electric field. The magnitude of the areal strain generated by the sample (up to 163% at 160 MV m\(^{-1}\)) is comparable to those generated using the same dielectric AE but different electrode materials (e.g., ≈100% at the same electric field for 250% prestrained DEAs using...
carbon grease and gel in ref. [48]). Figure 3b shows the measured frequency response of the actuator (applied voltage 3 kV). The magnitude of the actuation decreases with an increase in frequency, and reaches almost above at 10 Hz. This is due to the presence of viscoelasticity in both conductive AE and dielectric AE.[49] Similar behavior is observed for the same type of DEA as that reported in ref. [50], where the amplitude becomes almost zero when the frequency is below 10 Hz. These results suggest that the conductive AE is applicable to DEAs and can be used to replace the electrode materials.

Because the structure of DEA mentioned earlier is identical to that of a capacitor, it can be used as a sensor to detect deformations as a change in capacitance. Figure 1d–f shows a capacitive strain sensor made of the conductive AE and dielectric AE. Highly stretchable strain sensors are useful in soft robots and wearable devices to detect their large deformations (strain >100%).[15] especially the capacitive type exhibits excellent characteristics, such as high linearity and repeatability, fast response, and thermal tolerance.[19] When uniaxial loading is applied, the sensor electrodes elongate and their surface area increases, while the thickness of the dielectric decreases, resulting in changes in capacitance. The sensor response (i.e., capacitance $C$) involving these deformations is expressed as $C = C_0(\varepsilon + 1),[19]$ where $C_0$ is the reference capacitance and $\varepsilon$ is the applied strain. This indicates that the sensor response is proportional to the strain, and the sensitivity (gauge factor), expressed as $(\Delta C/C_0)/\varepsilon$, is theoretically equal to 1. The sensor fabricated in this study has an overlap area of the electrodes of 40 mm length and 12 mm width, and the unstrained value of capacitance for the three samples is 36.0 ± 0.4 pF. As expected, the sensor exhibits high linearity in its response ($R^2 = 0.995$) for a strain of up to 100%, as shown in Figure 4a. The gauge factor is 0.98 at 100% strain, matching the theoretical expression discussed earlier. These characteristics are retained under multiple cycles of 50% strain (Figure 4b), displaying good repeatability of the sensor with low hysteresis (drift error at 0% strain is 1.1%), like other sensors of the same type.

![Figure 4. Characterization results of the capacitive strain sensor.](image-url)

**Figure 3.** Characterization results of DEA. a) Areal strain as a function of applied voltage. Three samples are measured and the average is reported for each type. b) Areal strain as a function of driving frequency (applied voltage 3 kV).
Electrically driven stretchable pumps are a promising technology for soft robotics as they can remove the need of traditional rigid pumps, which tend to make the system bulky. The stretchable pumps exploit the principle, called electrohydrodynamics, where the electric charge injection and electric fields accelerate molecules in a dielectric fluid, leading to a net flow in a channel. Figure 1g–i shows a stretchable pump made of the conductive AE and dielectric AE, which has a similar size to the one presented in the previous study (75 mm long, 19 mm wide, and 1.5 mm thick). While the previous study uses PDMS, which requires blade-casting and thermal-curing, our pump only comprises off-the-shelf AEs, enabling faster fabrication. We characterize the stretchable pump in terms of pressure and flow rate as functions of the applied voltage. As a dielectric fluid, we choose to use FC-40 (3M). The result is shown in Figure 5, where the pump generates pressure and flow rate that grow quadratically with increasing voltage, and reach 0.11 ± 0.08 kPa and 20 ± 4 μL s⁻¹ at 7 kV, respectively. These values are in the same order of performances as that demonstrated by the pump in a previous study (0.4 kPa and 19 μL s⁻¹ at 5.3 kV). Note that the performance of an AE-based pump can be improved by optimizing the design parameters, such as the electrode gap and channel thickness. Still, the result obtained here shows the compatibility of the conductive AE for stretchable pumps, and thus potential for devices to interact with fluids.

To demonstrate the potential of our method for soft robotic systems, we develop a wearable device that has multiple functionalities (Figure 6a). It has a layered structure made of a conductive AE and a dielectric AE that contains sensing and actuation parts, as shown in Figure 6b. The former functions as a capacitive sensor to detect deformations in a human finger (in this study, the index finger). The latter acts as a haptic device under AC voltage, generating vibrations on the ball of the finger, and as an electroadhesion device when subjected to DC voltage, allowing it to adhere to external objects. Electroadhesion is an electrically controlled technology that works via the attraction of electric charges induced at the interface between the device and the adhered surface. Even though the device has a rich functionality, the fabrication time required is ≈15 min. As shown in Figure 6c, the device is able to detect the bending of the finger as changes in the capacitance (see Video S2, Supporting Information, for the operation). We have also confirmed that the vibration can be felt when AC voltage is applied to the actuation part. To quantify these haptic characteristics, the acoustic pressure is measured for driving frequencies ranging from 250 to 350 Hz (voltage of 3 kV). Human tactile detection is the most sensitive within this frequency range. Figure 6d shows the measured acoustic pressure, in which the generated vibration is visible across the tested driving frequency range. Then, we test the electroadhesion functionality by applying a DC voltage of 3 kV. As shown in Figure 6e, an object (a piece of paper) is successfully picked and placed through electroadhesion (see Video S3, Supporting Information, for the operation). The developed wearable device demonstrates how our method readily enables the integration of functional elements in a single layered structure. Combination of detection of deformations in a human finger and haptic vibration may serve as an interface for virtual reality and remote operation. Moreover, electroadhesion would extend the ability for handling by allowing us to adhere objects directly, which is otherwise difficult for human fingers.

We have characterized the mechanical and electrical properties of an off-the-shelf conductive AE as an electrode material for a rapid fabrication of soft matter systems and stretchable devices. Together with an off-the-shelf dielectric AE, the adhesive nature of the conductive AE allows layer-by-layer fabrication associated with laser cutting, which leads to rapid production of various stretchable devices without the need of material preparation, patterning, and curing. The soft transducers fabricated based on this strategy, DEAs, capacitive strain sensors, and stretchable pumps, have demonstrated comparable performances to those reported in the literature using other materials, illustrating the high applicability of the conductive AE. Moreover, the wearable device has exhibited multiple functionalities, which validates the effectiveness of our strategy for soft robotic systems. As the current study focuses on the basic properties and performance of the material and devices, respectively, future work will further investigate the characteristics such as influence of degradation and environmental factors, including humidity and temperature. Moreover, investigation of material combinations remains as an important aspect. Finally,
development of other soft/stretchable devices will bring additional insights on the potential applications based on the presented fabrication strategy, which is expected to advance the creation of future soft matter systems.

**Experimental Section**

**Stress–Strain Characterization:** A conductive AE (Adhesive Research, ARcare 90366) was cut into the shape of a tensile specimen (ISO 37:2017, Type 1A) using a laser machine (Trotec, Speedy 300). The dimensions of the specimen were 70 mm gauge length and 5 mm width. The adhesive surface of the conductive AE was then attached to a water-soluble tape and the protective film was peeled off without causing any damage. This water-soluble tape was used only in this experiment to obtain a free-standing specimen of the conductive AE. After dissolving the tape by soaking in water for 24 h, followed by drying for 10 h, the sample was put in a universal testing machine (Shimadzu, AGS-20NX) with holders made of a 5 mm-thick acrylic plate. The tensile speed was set to 60 mm min\(^{-1}\). With this procedure, six samples were measured. Curve fitting of the Yeoh hyperelastic material model was performed using a MATLAB script.

**Electrical Resistance–Strain Characterization:** The conductive AR was cut into a strip with dimensions of 70 mm length and 5 mm width. Together with holders made of a 5 mm-thick acrylic plate, the sample was placed on a linear motorized stage (Zaber, X-LRT1000DL) controlled by a personal computer (PC) and a microcontroller (Arduino, Arduino UNO). A conductive tape was attached to the sample to measure and record the electrical resistance through a multimeter (Keithley, 2100) and PC. The tensile speed was set to 60 mm min\(^{-1}\).

**Fabrication and Characterization of DEAs:** A dielectric AE (3M, VHB 4905) with protective films on both sides was cut into a circle (diameter of 45 mm) using a laser machine and prestrained using a stretcher. Subsequently, the stretched AE was held by an acrylic frame (inner diameter 45 mm). Laser-cut conductive AE with an electrode shape of diameter 10 mm was attached on both sides of the dielectric layer. After removing the protective film of the conductive AE, a conductive tape was placed on it for establishing the electrical resistance through a multimeter (Keithley, 2100) and PC. The tensile speed was set to 60 mm min\(^{-1}\). In the characterization with DC driving voltage, a transparent sheet with marking was used to ensure the alignment of the electrodes. The fabrication time required to arrive at this stage from the material cutting stage was \(\approx 15\) min (cutting time of \(\approx 5\) min). In the characterization with DC driving voltage, a CCD camera (HOZAN, L-835) connected to the PC was used to measure and record the areal strain of the electrodes. The fabricated DEA was actuated through a function generator (Matsusada,
eK-FGJ) and a high-voltage power supply (Matsusada, HEOPS-5B6). In the characterization with an AC driving voltage, instead of the CCD camera, a laser displacement meter (Optex FA, CDX-L15) was used to measure the deformation of the electrodes in the thickness direction.

**Fabrication and Characterization of Capacitive Strain Sensors:** The fabrication process and structure of the sensor are shown in Figure S2, Supporting Information. Both conductive and dielectric layers with protective films were cut using the laser machine and laminated sequentially. Every layer had the same outline geometry, which ensured their alignment. During these steps, a conductive tape was attached to the conductive AE to establish an electrical connection. After holding frames made of an acrylic plate were placed, the device was ready for testing. The fabrication time required to arrive at this stage from the material cutting stage was ≈15 min (cutting time of ≈5 min). The electrode dimensions were 50 mm length and 12 mm width. The dielectric layer had outline dimensions of 60 mm length and 16 mm width. The overlap area of the electrodes was 40 mm long and 12 mm wide. The sensor was placed on the linear motorized stage controlled by the microcontroller and PC. The capacitance value was measured and recorded through an LCR meter (GW Instek, LCR-6002, sampling frequency 40 Hz) and a PC. With this setup, three sensors were measured at a speed of 1 mm s⁻¹. In the 10⁴ cycle test, the sample was measured at a strain rate of 25% s⁻¹.

**Fabrication and Characterization of Stretchable Pumps:** The fabrication process and structure of the pump are shown in Figure S3, Supporting Information. All layers, including the interdigitated electrodes made of the conductive AE and other structure parts made of the dielectric AE, were cut using the laser machine. Every layer had protective films that were removed after the cutting. These layers were attached sequentially using an alignment jig made of an acrylic plate, which had a hole that was identical to the outline geometry of the pump. A transparent sheet with the marking of electrode geometry was placed at the bottom of the jig to ensure the alignment further. A silicone tube (inner diameter 2 mm) was then connected to each channel hole using an adhesive sealant ( Dow Corning, 734), and the sample was ready for testing. The fabrication time required to arrive at this stage from the material cutting stage was ≈30 min (cutting fluid time was ≈5 min, and curing time of the sealant was ≈15 min). A dielectric liquid (3M, FC-40) was filled in the channel and tubes. The fabricated stretchable pumps were powered by a high-voltage DC/DC converter (XP Power, CB101). The pressure was measured from the difference in the liquid level in the tubes, which was recorded using a camera (Nikon, D3500). The flow rate was measured from the speed of liquid level difference.

**Fabrication and Testing of Wearable Device:** The fabrication process and structure of the wearable device are shown in Figure S4, Supporting Information. Similar to the other cases mentioned earlier, the device consisted of layers of the conductive AE and dielectric AE, which were cut using the laser machine. After cutting, the layers were laminated one-by-one using an alignment jig made of an acrylic plate. Finally, a piece of protective film was placed above the actuation part to hinder the inherent stiction of the material in this particular domain. The fabrication time required to arrive at this stage from the material cutting stage was ≈15 min (cutting time of ≈5 min). While testing the sensing functionality, the capacitance was detected using an LCR meter (GW Instek, LCR-6002, sampling frequency 10 Hz). While testing the electrodhesion functionality, the device was driven by a high-voltage power supply (Matsusada, HEOPS-5B6). While testing the haptic functionality and measuring the acoustic pressure, an open source high-voltage power supply (Matsusada, HEOPS-5B6). During these steps, a conductive tape was attached to the conductive AE to establish an electrical connection. After holding frames made of an acrylic plate were placed, the device was ready for testing. The fabrication time required to arrive at this stage from the material cutting stage was ≈15 min (cutting time of ≈5 min). The electrode dimensions were 50 mm length and 12 mm width. The dielectric layer had outline dimensions of 60 mm length and 16 mm width. The overlap area of the electrodes was 40 mm long and 12 mm wide. The sensor was placed on the linear motorized stage controlled by the microcontroller and PC. The capacitance value was measured and recorded through an LCR meter (GW Instek, LCR-6002, sampling frequency 40 Hz) and a PC. With this setup, three sensors were measured at a speed of 1 mm s⁻¹. In the 10⁴ cycle test, the sample was measured at a strain rate of 25% s⁻¹.

**Supporting Information**

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

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**Conflict of Interest**

The authors declare no conflict of interest.

**Keywords**

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