Fabrication of Highly Sensitive Piezocapacitive Pressure Sensors using a Simple and Inexpensive Home Milk Frother

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To improve the sensitivity of piezocapacitive pressure sensors, the thickness of the dielectric layer must vary with exposure to a weak force, and the mechanical modulus must be low. We propose a simple method for trapping air bubbles in an elastomer to reduce the modulus of the elastomer. The sensitivity of the pressure sensors fabricated from the air bubble-trapped elastomer is approximately 10 times better than that of a pressure sensor without air bubbles. The pressure sensor with air bubbles has a very high linear response to external pressure changes. We also demonstrate that the pressure sensor fabricated from the air bubble-trapped elastomer can detect the dynamic loading and unloading pressure of a small Lego toy and a small M6 bolt. These results show that our pressure sensor based on the air bubble-trapped elastomer can be used to detect applied pressures or contact forces of electronic skin (e-skin).

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I. INTRODUCTION

Stretchable electronic skin (e-skin) has drawn recent attention due to its applicability to wearable health monitoring devices, sensitive tactile information displays, prosthetic limbs, and multifunctional robot skin [1–4]. E-skin converts external forces into a signal that can be read digitally [5]. This digital signal consists of the signal from resistive [2], piezoelectric [6], triboelectric [7], and capacitive [1,3] changes with external pressure. Resistive sensors detect the resistance change due to the change in the distance between the conductive fillers in the elastic composite under external pressure. When pressure is applied, the interparticle spacing between the conductive fillers decreases, enhancing electron tunneling and thereby lowering the effective resistance. Piezoelectric and triboelectric sensors detect the piezoelectric charge and triboelectric charge generated by external pressure, respectively [6,7]. Finally, capacitive sensors detect the capacitive change resulting from the change in the dielectric thickness under external pressure. However, sensors based on resistive, piezoelectric, and triboelectric properties are typically highly nonlinear [1,8]. On the other hand, capacitive sensors have a linear response. Thus, this study examines capacitive sensors.

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The capacitance per unit area for capacitance sensors is given by

\[ C = \frac{\varepsilon_r \varepsilon_0}{d} \]  

(1)

where \( \varepsilon_r \) is the relative dielectric constant of the material, \( \varepsilon_0 \) is the permittivity of free space, and \( d \) is the thickness of the dielectric layer [9]. If the dielectric layer is an elastomer, the dielectric thickness is affected by the external pressure and the capacitance from Eq. (1) will change. To achieve high sensor sensitivity, which requires a good signal-to-noise ratio, the thickness of the dielectric layer must vary with exposure to a weak force, and the mechanical modulus must be low. Therefore, attempts were made to create air gaps in the elastomer to enhance the change in force and reduce the modulus. To make air gaps, Z. Bao et al. used an array of pyramidal microstructured elastomers [1,10], and H. S. Lee et al. used a microwrinkled elastomer [11]. Such a microstructure on the elastomer surface suffers from a change in contact area due to deformation of the elastomer under applied pressure. Moreover, these methods for making air gaps are complex.

In this study, we create air bubbles inside the elastomer to eliminate the effects from changing the contact area that occur when force is applied. We propose a simple method for trapping air bubbles inside an elastomer using a home electric milk frother. For comparison, the properties of the elastomer without air bubbles are also investigated. Finally, we demonstrate the usefulness of...
the air bubble-trapped elastomer by detecting lightweight objects such as a Lego toy and an M6 SS bolt.

II. EXPERIMENT

A. Air bubble-trapped Ecoflex templates

Air bubble-trapped Ecoflex templates are prepared using an inexpensive home milk frother [see Fig. 1(a), MMF-003, Xinxing Winter Electrical Appliance Co.] and by controlling the viscosity of the Ecoflex mixture (00-30, Smooth-On Inc.). Because the home milk frother cannot be applied to high-viscosity Ecoflex mixtures (i.e., the mixture of the prepolymer and curing agent), the viscosity of the Ecoflex mixture is reduced by adding toluene (Aldrich Inc.), which has a low viscosity. As shown in Fig. 1(b), the degree of air bubbles is controlled by the amount of toluene. Finally, the Ecoflex mixtures are prepared by mixing a prepolymer, a curing agent, and toluene in weight ratios of 1:1:0, 1:1:0.5, 1:1:1, and 1:1:1.5. After the Ecoflex mixtures are mixed with a Thinky mixer (ARE-310, Thinky Corp.) for 5 min, the Ecoflex mixtures are cast in a square SS mold with a width of 60 mm, a length of 60 mm, and a thickness of 1 mm. After casting, the mixture is quickly cured on a hotplate at 100 °C for 1 h [12].

B. Characteristics of the air bubble-trapped Ecoflex pressure sensors

Ecoflex pressure sensors are made by placing the Ecoflex sheets between a circular SS electrode with dimensions of 11.4 × 1 mm² (i.e., diameter × height, top electrode) and a square brass electrode with dimensions of 30 × 30 × 15 mm³ (i.e., length × width × height, bottom electrode). The rigid SS electrode is used as the top electrode to exclude deformation of the electrode during measurement. An Agilent 4980A Precision LCR meter is used to measure the piezocapacitive responses of the air bubble-trapped Ecoflex pressure sensors to various stimuli. The pressure sensing capabilities of the sensors are characterized using a computer-controlled homemade sensor measurement system with a z axis moving stage (LNR50SE, Thorlabs Corp.) with a movement range of 50 mm and a force gauge (M7-05, Mark-10 Corp.) with a capacity of 250 gF. The moving stage moves at a speed of 1 mm/s. The load applied to the force gauge is measured, and the corresponding pressure is calculated by dividing by the area of the top electrode.

III. RESULTS AND DISCUSSION

A viscosity analysis (Haake Modular Advanced Rheometer System) is performed on the Ecoflex mixtures with various toluene contents. As shown in Fig. 2, the viscosity of the Ecoflex mixtures is controlled by

FIG. 1. Digital camera images of (a) the home milk frother and (b) the Ecoflex sheets with 1:1:0, 1:1:0.5, 1:1:1, and 1:1:1.5 ratios. Optical microscopy images of the sheets with (c) 1:1:0, (d) 1:1:0.5, (e) 1:1:1, and (f) 1:1:1.5 ratios.

FIG. 2. Viscosity as a function of shear rate for sheets with 1:1:1.5, 1:1:1, 1:1:0.5, 1:1:0, and 0:0:1 ratios.
the content of toluene. The viscosities of 1:1:0, 1:1:0.5, 1:1:1, 1:1:1.5, and 0:0:1 (i.e., the weight ratios of prepolymer, curing agent, and toluene) mixtures are 7353, 848, 301, and 0.544 cP, respectively [13]. Due to the low viscosity of toluene, the viscosity of the Ecoflex mixtures decreases, which benefits the creation of air bubbles inside the Ecoflex using the home milk frother. When creating air bubbles in the Ecoflex mixtures under reduced viscosity, the air bubbles easily merge with other bubbles, and the size of the bubble increases. Larger bubbles are lighter and move easily to the surface. When bubbles approach the interface between the Ecoflex and air, they burst, and the bubble’s cavity collapses [14]. To trap air bubbles inside the Ecoflex mixtures, the SS mold plates are quickly placed on a hot plate at 100 °C after molding. When the Ecoflex mixtures are placed on the hot plate, the viscosity increases as toluene evaporates and the Ecoflex mixtures cures. As the viscosity increases, the air bubbles do not merge with other bubbles and cannot move to the surface. Finally, the bubbles became trapped inside the Ecoflex template. For this reason, the lower-viscosity Ecoflex has larger bubbles, as shown in Figs. 1(c)–1(f). Bubbles are not trapped inside the Ecoflex template because of the lower viscosity when the ratio is greater than 1:1:1.5. The densities of the Ecoflex mixtures with ratios of 1:1:0, 1:1:0.5, 1:1:1, and 1:1:1.5 are 1061, 990, 843, and 755 kg/m³, respectively. The

![Graphs showing relative capacitance change as a function of step-by-step stress and normal stress for different ratios.](image)

**FIG. 3.** Relative capacitance change ($\Delta C/C_0$) as a function of (a) the step-by-step stress in the 0–10.20 kPa range and (b) the normal stress for sheets with 1:1:1.5, 1:1:1, 1:1:0.5, and 1:1:0 ratios.

![Graphs showing durability test results.](image)

**FIG. 4.** Durability test under an applied stress of 4.64 kPa over more than 35 cycles for sheets with (a) 1:1:0, (b) 1:1:0.5, (c) 1:1:1, and (d) 1:1:1.5 ratios. Stress responses during single cycles showing the response and release times for sheets with (e) 1:1:0, (f) 1:1:0.5, (g) 1:1:1, and (h) 1:1:1.5 ratios.
densities of the Ecoflex mixtures decrease as the amount of toluene increases. This means that as the amount of toluene increases, the total volume of air bubbles in the Ecoflex mixtures increases.

The step-by-step performance of the Ecoflex pressure sensors with various toluene contents is evaluated with a normal stress of 0–10.20 kPa [15]. As shown in Fig. 3(a), the relative capacitive change (ΔC/C0) is measured while applying a step stress to the Ecoflex mixtures between the top electrode and the bottom electrode for 10 s, during which the relative capacitive change (ΔC/C0) increases as the step stress increases. Because the Ecoflex thickness decreases as the step stress increases, the capacitance increases by Eq. (1).

The pressure sensitivity, defined as the G factor, of the Ecoflex pressure sensors is determined by the slope of the relative capacitive change (ΔC/C0) vs the normal stress [11,16]. As shown in Fig. 3(b), the pressure sensitivities increase with the amount of toluene, and the G factors of 1:1:0, 1:1:0.5, 1:1:1, and 1:1:1.5 are 6.5 × 10^{-4}, 1.9 × 10^{-3}, 3.3 × 10^{-3}, and 5.5 × 10^{-3} kPa^{-1}, respectively. The Ecoflex template with air bubbles improves the sensitivity by approximately 10 times over that without air bubbles. Thus, the response or sensitivity to external stress is significantly improved because the modulus of the Ecoflex mixtures decreases with decreasing density of the Ecoflex mixture due to air bubble formation inside the Ecoflex template [17]. Although the sensitivity of our sensor is lower than that with the previously reported highest sensitivity (i.e., 0.55 kPa^{-1} from Z. Bao et al. [18]), previously reported sensors are nonlinear [18–20], while our sensors have very high linearity. If the device has nonlinearity, such as in Ref. 18, one of two regions (i.e., 0–2 kPa and 2–7 kPa) may be used. However, both can be used in our case due to the linearity (i.e., 0–10 kPa). This linearity and improved sensitivity show that the air bubble-trapped Ecoflex template is useful as a pressure sensor.

The operating reliabilities, response times, and release times of the Ecoflex pressure sensors are shown in Fig. 4. The device durability is obtained by measuring the relative capacitor change (ΔC/C0) of the devices over 35 repeated load-unload cycles with an applied stress of 4.64 kPa. The pressure sensitivity of the Ecoflex pressure sensors increases with an increasing amount of toluene, providing relative capacitor changes (ΔC/C0) of 0.0031, 0.0078, 0.014, and 0.026, respectively. The response and release times for the Ecoflex pressure sensors range from 351 to 386 ms and are similar. This result shows that air bubbles improve the sensitivity without changing the response and release times.

We use the Ecoflex pressure sensor with an optimal 1:1:1.5 composition to detect the dynamic loading and unloading pressure of a small Lego toy (3.0 g) and a small M6 bolt (4.5 g) with a z-axis moving stage. A change in the capacitance is detected, as shown in Fig. 5. High signal-to-noise ratios are obtained from pressure measurements, which demonstrate the high sensitivity of our Ecoflex pressure sensor.

**IV. CONCLUSION**

In this study, we demonstrate a simple method for trapping air bubbles in an elastomer to enhance the sensitivity of the resulting pressure sensor. The sensitivity of the Ecoflex pressure sensor fabricated from the air bubble-trapped elastomer is approximately 10 times better than that of the pressure sensor without air bubbles. The Ecoflex pressure sensor with air bubbles has a very high linear response to external pressure changes. We also examine the ability of the Ecoflex pressure sensor with air bubbles to detect the dynamic loading and unloading pressure of a small Lego toy and a small M6 bolt. These results suggest that our pressure sensor based on the air bubble-trapped elastomeric template, fabricated through a simple and inexpensive process using a home milk frother, constitutes an effective device structure for enabling e-skins capable of detecting applied pressures or contact forces.

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