Laser-bonding of FEP/FEP interfaces for a flexible manufacturing process of ferroelectrets

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Abstract. This paper presents an optimized laser-bonding process for piezoelectric energy-harvesters based on thin fluorinated-ethylene-propylene (FEP) foils, using an ultra-short-pulse (USP) laser. Due to the minimized thermal stress in the material during bonding, achieved by pulse durations of few picoseconds, we created seams down to 40 µm width without generating holes in the 12.5 µm thick FEP-foils. Using a galvanometer scanning system allowed for fast bonding-speed up to several centimeters per second, making the process also suitable for large structures and areas. The achieved bond strength of the seams under influence of shearing stress was examined using tensile testing, which showed a sufficient strength of about 25% of the maximum strength of an unbonded, single layer of FEP.

1. Introduction
In the last decade, there has been a significant increase in the research on vibration-based energy harvesting using ferroelectrets [1]. Generally, these electrets consist of artificial air voids, which were electrically charged to act as microsized electric dipoles. A common representative is fluorinated-ethylene-propylene (FEP), which is known for its high thermal and chemical stability as well as its high piezoelectric d33-coefficient [2]. In principle, FEP-based ferroelectrets consist of two interconnected FEP-foils in which cavities of various geometries can be impressed [3, 4, 5]. The bonding of the FEP-foils is a crucial step, as temperatures above the melting point of FEP around 280 °C are necessary, which can cause damage to the material. Beside thermal fusion-bonding, only few different processes have been examined: ultrasonic induced bonding [6], chemical bonding [7] and laser-bonding [8]. While the first two methods are not applicable for bonding on small, selective areas, laser-bonding has the potential for fast and precise bonding of FEP-foils. Up to this point only one publication of Fang et al. has addressed this challenge by replacing the thermal fusion-bonding with laser-bonding [8]. Circular holes with bonded edges were created by melting through two layers of FEP utilizing an infrared laser. The drawback of this approach is that the minimal size of the bonding area is in the millimeter-range and that the material itself is damaged during bonding. To overcome these disadvantages, we integrated ultra-short-pulse (USP) laser-bonding into the production process of FEP-based ferroelectrets.
2. Processing of FEP-based piezoelectrets

Prior to the laser-bonding process, FEP-foils were microstructured in a thermoforming process [9]. For the fabrication process of the thermoforming-master, a 45 µm thick layer of the photoresist SU-8 100 (Micro Chem Corp., Westborough, USA) was spin-coated and photolithographically structured on a four-inch borosilicate glass wafer with a thickness of 700 µm (Schott AG, Mainz, Germany). The width of the produced structures was 500 µm with a spacing of 250 µm, which depends on the used photomask. The thermoforming process was performed with a 12.5 µm thick FEP-foil, which was placed and flattened on the thermoforming master. On top of that, an 800 µm thick layer of natural rubber was used as buffer layer. Under a static pressure of 1 MPa applied for 15 min, the foil was thermoformed at 130 °C. After cooling down to room temperature a second foil was placed on top of the structured foil and bonded with the process described in chapter three. In the last step, the connected FEP foils were sputtered with 100 nm of copper and charged by applying a sawtooth DC-voltage of several kilovolts between the electrodes with a period of 2 seconds for a total time of 10 seconds. The complete production process is depicted in Figure 1.

![Figure 1](image)

**Figure 1.** Schematic illustration of the fabrication process of the ferroelectrets: (a) Photoresist SU-8 100 was spin-coated and photolithographically structured on a borosilicate glass wafer. (b) A 12.5 µm thick FEP-foil was placed on top of the master and (c) thermoformed in a heat press. (d) A second foil was placed on top of the thermoformed foil and both foils were selectively laser-bonded. (e) Bonded foils were removed from the master, sputtered with 100 nm copper on both sides and electrically charged.

3. Laser-bonding of FEP/FEP interfaces using pico-second laser

USP laser-bonding of transparent materials is commonly achieved by a heat accumulation at the interface between the joining partners which is initiated by a nonlinear absorption of high repetition rate laser pulses. There are different reports showing a wide range of processable materials from glass to polymers [10, 11]. In our study, we used an ultra-short-pulse laser (Pharos-10-600: Light Conversion, Vilnius, Lithuania) with a fundamental wavelength of 1,028 nm having an adjustable pulse duration from 220 fs to 15 ps and a variable repetition rate up to 610 kHz. The laser beam with a diameter of 3.7 mm (1/e²) is positioned by a galvanometer scanner (Rothor AR800; Newson Engineering, Dendermonde, Belgium) in combination with a telecentric f-Theta lens with a focal length of 100 mm (Linos F-Theta Ronar; Qioptiq Photonics, Göttingen, Germany) resulting in a focal spot diameter of 35 µm. The focal height is controlled by a linear z-stage (Pro 165; Aerotech, Pittsburgh, USA). A precise positioning is achieved by an offset-camera. A schematic illustration of the laser-bonding setup is shown in Figure 2.
Transparent FEP-foils with a thickness of 12.5 µm were bonded together on top of a SU-8 master. Due to the higher absorptivity of the substrate material an ablation of the photoresist was initiated and enabled thereby a heating, melting and bonding of the thin FEP-foils. Samples were processed at a pulse duration of 1 ps, a repetition rate of 100 kHz, a laser power of 680 mW and a scanning speed of 10 mm/s.

![Figure 2. (a) Schematic illustration of the laser-bonding setup and (b) scheme of the process depicting the areas where the FEP-layers will be bonded.](image)

4. Characterization

The produced ferroelectrets were characterized in three ways: optical inspection of the voids and bonding lines, mechanical tensile testing of the bond seams and electrical characterization to test the quasistatic response of the material.

4.1. Optical inspection

For optical inspection cross-sectional micrographs of the voids were taken and dark-field images of the bonding lines were used to determine the width of the bonding lines. These micrographs are depicted in Figure 3.

![Figure 3. (a) Cross-sectional micrograph of two laser-bonded FEP-foils. The void-width is 500 µm with a spacing of 250 µm. (b) Top-view of the bonded areas.](image)
As can be seen in Figure 3 (a), the height of the void is about 45 µm which corresponds well with the produced height of the SU-8 thermoforming-master. It can be seen, that the two foils were bonded together and no holes were generated in the foils. The minimal bond-width of the laser-bonded areas is approximately 40 µm (see Figure 3 (b)). It can be enlarged by producing multiple seams close to each other.

4.2. T-peel test
To characterize the bond seam in more detail, tensile tests (EZtest EZ-L; Shimadzu Deutschland GmbH, Duisburg, Germany) were performed: a classic tensile test on unbonded FEP and a T-peel-test according to Figure 4 (a). The used samples had a width of 1 cm and a length of several centimeters. Samples for the T-peel-test included at least ten bonding lines, so that a couple of laser-bonds could be measured in each experiment. As reference, single FEP-foils were used in a normal tensile test, which resulted in a maximum force of 5 N before the FEP ripped, as can be seen in Figure 4 (b). Evaluating the bond strength for different laser powers yielded an optimum of 1.25 N ± 0.1 N at a laser-power of 680 mW. Increasing as well as decreasing the power resulted in smaller values of the bond strength.

Figure 4. (a) Scheme of the T-peel-test for the evaluation of the bond strength. (b) Force-displacement curve of a tensile test using a single layer of FEP. The maximum force before breaking of the FEP was about 5 N. The width of the samples was considered in the measurement. (c) Result of the T-peel-test for three bonded lines. The maximum sheer-force was about 1.25 N, which is 25 % of the maximum strength of a single layer of FEP.

4.3. Quasistatic measurement
Using a quasistatic approach, the produced piezoelectrets were characterized with respect to their piezoelectric properties. A load of 1.5 kPa was attached and removed for ten times on each piezoelectret. The generated charge was measured on a Spider 81B vibration-controller (Crystal Instruments, Santa Clara, USA) with integrated charge amplifier. With this setup a piezoelectric d_{33}-coefficient with more than 1,000 pC/N has been reached. These measurements were not carried out for the quantitative analysis of the d_{33}-coefficient but to confirm the quality of the bond seams and the functionality of the device. Holes in the seams would provide a short cut between the copper-coated sides, whereby inhibiting electric charging.
5. Conclusion
The goal of this research was to develop a fast and reproducible bonding-process for microstructured ferroelectrets. The presented process using an USP-laser shows good results with seams down to 40 µm. T-peel-testing showed, that after parameter optimization the bond strength is at about 25 % of the maximum strength of an unbonded FEP-foil. As a major advantage, the shape of the produced seams is not limited, but can be applied to any geometric shape in addition to the line shape. Furthermore, this process can easily be transferred to other FEP-based energy-harvesting-systems including triboelectric or electrostatic generators.

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