Piezoelectric cellular polymers as sensors or air-borne ultrasonic transducer: Property adjustment by foam-structure and geometry variations

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Abstract:

Electrically charged polymers with a cellular foam structure show piezoelectric properties and are discussed as so-called ferroelectrets. Research requests are an optimization of the ultrasonic properties of ferroelectrets such as low thickness-extension resonance frequencies as well as high operating voltages for the final transducer. We present two approaches for modification of ferroelectrets which fulfill these requirements. One approach is the preparation of thicker transducer films in order to decrease the resonance frequencies, another approach is the use of dielectric layers in hybrid transducers in order to shift the onset for dielectric breakdowns within the voided structure. Beside the film processing, the electrical poling as well as the resulting transducer properties are discussed.

Key words: piezoelectric, piezoelectric sensor, piezoelectric actuator, ultrasonic transducer.

Introduction

Piezoelectric polymers are widely used as sensor and actuator materials, while research in material development is focused on dipolar orientation processes, space-charge trapping mechanisms and electrical-mechanical interactions. The main working horse in the field of piezoelectric polymers are materials such as polyvinylidene fluoride (PVDF) and its copolymers with trifluoroethylene (P(VDF-TrFE)) and hexafluoropropylene (P(VDF-HFP)) [1-5]. PVDF and its copolymers show pronounced piezoelectric activities with piezoelectric coefficients in the range of typically 10 to 30 pC/N for the piezoelectric thickness (33) or in plane (31) effects. For application of polymers as ultrasonic transducers, often the piezoelectric 33-effect is used. However, typical transducer film thicknesses of some ten to some hundred µm and an elastic modulus in the range of 2 to 10 GPa leads to thickness-extension resonance frequencies in the range of some MHz to hundred MHz. In addition, an acoustic impedance of 3×10^6 kg/m^{2}s allows an optimal acoustic matching to water but leads to an non-optimal coupling e.g. to air if such piezoelectric materials should be operated as air-borne ultrasonic transducer.

Ferroelectrets show completely other properties if they are used as ultrasonic transducers. Ferroelectrets are composites which consist of space-charge electrets arranged in a foamed structure, while the voids are usually filled with air [6-9]. The physical principle of ferroelectrets is: (i) an electrical poling of the voided polymer structure leads to trapped charges of opposite polarities located at opposite void surfaces within the cellular structure and thus to huge electrical dipoles, (ii) the soft polymer-air composite structure allows a deformation under mechanical load which leads to the change of the dipole sizes and (iii) thus to the generation of an electrical signal during the deformation of the composite structure. The detected electrical signals are mainly linear depending on the applied mechanical load. Thus, the systems are discussed as piezoelectric transducers. Beside earlier studies on polypropylene (PP), the material basis was extended to other space-charge electrets such as polyethylene terephthalate (PET) [10], polyethylene naphthalate (PEN) [11], fluorinated ethylene propylene copolymers (FEP) [12] as well as cycloolefine polymers (COP) and copolymers (COC) [13].

The advantages of ferroelectrets are their cheap basis materials which allow large-area processing of piezoelectric transducers and especially the interesting ultrasonic properties which originate from their low-elastic modulus combined with the air-filled composite structure. It was found that ferroelectrets exhibit a huge potential as sensor and actuator materials in air-borne ultrasonic transducers [14]. This evaluation is based on the determined thickness-extension resonance frequencies in the range of some hundred kHz to about 2 MHz, combined with a good acoustic coupling to air represented by an acoustic impedance in the range of 2 to 10×10^4 kg/m^{2}s. In addition the found piezoelectric activities are also relatively high, piezoelectric d_{33} coefficients between some ten and thousand pC/N or pm/V were reported for different kinds of ferroelectrets.

However, also for classical ferroelectrets made from PP with a cellular structure there is the interest in optimization of properties such as the reduction of the thickness-extension resonance frequency or the increase of the driving voltage during operation. Here we present two attempts which fulfill the above mentioned optimization scenarios.

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Ferroelectrets with reduced resonance frequency

The ultrasonic properties of ferroelectrets can be adjusted by an optimal electrical poling which defines the amplitude of the actuator and sensor signal and by variations of the transducer geometry, e.g. the thickness, as well as the inner microscopic structure which defines the elastic properties of the samples. The inner voided structure is varied by means of a gas diffusion expansion of an initial foamed polymer film [15-16]. Classical PP ferroelectrets can be processed in a broad variation containing relatively flat voids to round voids corresponding to high and low composite densities, respectively. A typical dependence of the elastic and electro-mechanical properties from the voided structure is shown in Fig. 1.

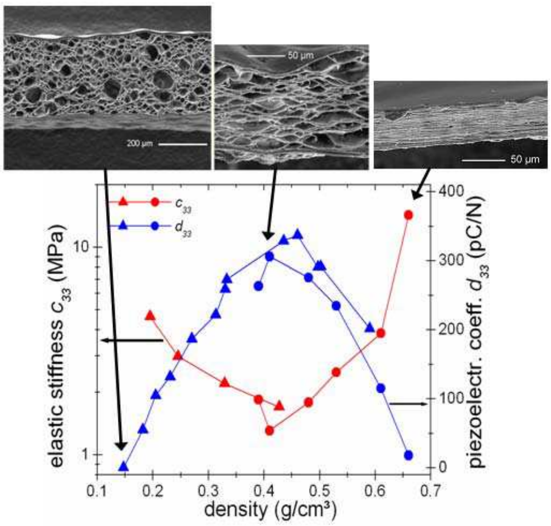

Fig. 1: Ferroelectrets with different voided structures: Dependence of the density, elastic stiffness and piezoelectric properties on the foam structure.

The underlying film thicknesses of the transducer films shown in Fig. 1 are in the range of 34 to 40 µm for high density / low expanded films and 230 µm for low density / maximum expanded films. The above mentioned films show thickness-extension resonance frequencies in the range of 600 kHz to 2 MHz, depending on the foam structure.

With preparation of initially thicker films then the above mentioned 40 µm thick transducer films we were able to produce ferroelectrets which similar void structures compared to that of the films shown above, but with thicknesses between about 90 and 340 µm. All other preparation steps such as expansion, electrical poling and metallization were employed in a similar way, like the preparation of the initially 40 µm thick films. As a result, those thicker transducer films shown thickness-extension resonances between 233 and 261 kHz and thus much lower resonance frequencies then the above mentioned initially 34 to 40 µm thick films.

Ferroelectrets with increased operating voltage

In order to obtain ferroelectrets with increased breakdown voltage we processed hybrid systems of classical ferroelectrets with a dielectric cover layer at one surface as schematically shown in Fig. 2. Here, the dielectric cover layer is made of polymethylmethacrylate (PMMA) processed from a liquid phase via spin coating on top of the ferroelectret film. Details about the processing and the available hybrid systems are given in [17].

Depending on the processing parameters during spin coating, the thickness of the PMMA layer can be adjusted between 1 and 16 µm. The initial thickness of the ferroelectrets before expansion was about 40 µm. The films were electrically charged in direct contact applying voltages up to 8 kV. This electrical poling leads to maximum piezoelectric activities of 165 pC/N and 195 pC/N for the pure and the hybrid ferroelectrets. More interesting is that the due to the PMMA coating layer the threshold voltage for dielectric breakdowns within the voids is shifted from about 3 kV for the pure ferroelectret films to about 4 kV for the hybrid ferroelectret films. This allows the use of hybrid ferroelectrets films in ultrasonic probes applying operating voltages up to 4 kV. In addition, the dielectric layer provides a mechanical load which lowers the overall thickness-extension resonance frequency. The measured thickness-extension resonance frequencies of hybrid ferroelectret transducers coated with different thick PMMA layer are shown in Fig 3.

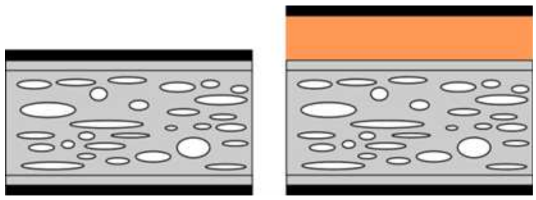

Fig. 2: Left picture: Schematic sketch of a classical ferroelectret covered with electrodes. Right picture: Schematic sketch of a hybid system of a dielectric PMMA layer (colored orange) processed onto a ferroelectret film.

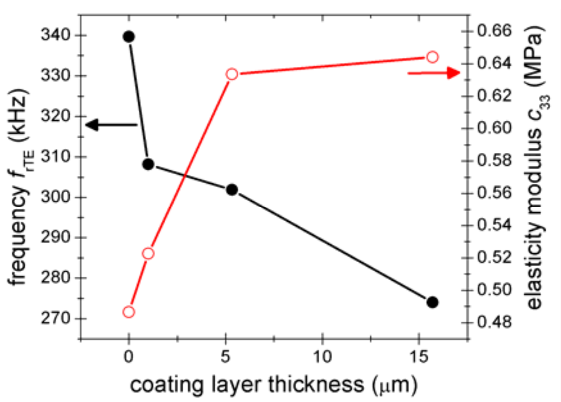

Fig. 3: Thickness-extension resonance frequencies of hybrid transducers consisting of a ferroelectret coated with different thick PMMA layer.

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Summary

In summary, two preparations of ferreoelctrets with lowered thickness-extension resonance frequencies are reported. In one case, the well known preparation steps of ferroelectrets with different voided structures are applied to voided films with an initially increased thickness. Here a broad variation of piezoelectrically active films with thickness-extension resonance frequencies down to 233 kHz are received. In a second case, classical 40 µm thick films were expanded afterwards coated with an additional dielectric layer. Depending on the thickness of the dielectric layer the thickness-extension resonance frequency is adjustable. Further more, the threshold for dielectric breakdowns within the voids is increased with the increase thickness of the coating layer which allows higher voltage operation of the ultrasonic transducer.

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