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Reducing the capacitance of piezoelectric film sensors

Martín G. González,[1,2,a)] Patricio A. Sorichetti,[1] and Guillermo D. Santiago[1]
[1]*Grupo de Láser, Óptica de Materiales y Aplicaciones Electromagnéticas (GLOMAE), Departamento de Física, Facultad de Ingeniería, Universidad de Buenos Aires, Paseo Colón 850, C1063ACV Buenos Aires, Argentina*
[2]*Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), C1425FQB Buenos Aires, Argentina*

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We present a novel design for large area, wideband, polymer piezoelectric sensor with low capacitance. The large area allows better spatial resolution in applications such as photoacoustic tomography and the reduced capacitance eases the design of fast transimpedance amplifiers. The metalized piezoelectric polymer thin film is segmented into N sections, electrically connected in series. In this way, the total capacitance is reduced by a factor $1/N^2$, whereas the mechanical response and the active area of the sensor are not modified. We show the construction details for a two-section sensor, together with the impedance spectroscopy and impulse response experimental results that validate the design. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4946770]

I. INTRODUCTION

Several ultrasound applications such as photoacoustic tomography, hydrophones, and vibration analysis require capturing wideband signals with low amplitude and phase distortion.[1] In addition, these applications benefit from the increased spatial resolution provided by a large area detector.[2] Usually, thin-film, wideband piezoelectric sensors are used at frequencies below the first mechanical resonance (sub-resonant regime). The mechanical resonance frequency can be raised by lowering the thickness of the device. However, for a given area, this leads to an increased capacitance, which is an undesirable feature because it complicates the design of the amplifying stages. The simplest model, for circuit analysis purposes, of a piezoelectric detector resembles a current source in parallel with a capacitor. Thus, if high-frequency operation is sought, it is necessary to resort to a transimpedance amplifier. The analysis of the amplifier with a capacitive signal source shows that it is necessary to use a compensating capacitor that lowers the frequency of the dominant pole to a value well below the gain-bandwidth product of the bare amplifier.[3] Even though, in principle, it is possible to use an adapting transformer, it requires a careful design to achieve wideband performance, the use of a linear core to reduce distortion and good shielding to avoid capturing unwanted signals. Therefore, the use of transformers is mostly restricted, in practice, to narrow-band applications, such as resonant detectors.

Our proposal considers a piezoelectric detector of area A and thickness t. The detector is split into N equal area sub-detectors on a common substrate. Each element is connected in series with its neighbor. In this way, the capacitance of each sub-detector goes as $1/N$ and, since N of them are connected in series, the total equivalent capacitance varies as $1/N^2$. This suggests that even a small number N of sub-detectors leads to an important reduction of the equivalent capacitance. Furthermore, since the open-circuit output voltage is N times larger, the action of splitting the detector is equivalent to including a step-up transformer of ratio 1:N. Figure 1 shows a qualitative electrical circuit of the split detector, valid at frequencies below the first mechanical resonance. The unsegmented electrode (UE) sensor is represented as a current source in parallel with a capacitance (Norton equivalent) or a voltage source in series with a capacitance (Thevenin equivalent). We resort to the last one to make a schematic of the segmented electrode (SE). It can be seen that the open-circuit total voltage is N times that of the UE detector and the total capacitance lowers to C/N^2. This arrangement does not change the active area or the mechanical response of the sensor.

II. MATERIALS AND METHODS

The sensor was implemented using a polyvinylidene difluoride (PVDF) thin film (PIEZOTECH CORP) with a thickness of 25 μm and metalized on both sides. The intensive parameters in the poling direction of the film at room temperature were determined using a non-resonant method described in Ref. 4. Table I shows the values at different frequencies of the piezoelectric coefficient (d_{33}), the elastic compliance at constant electric field (s_{33}), and the relative complex permittivity at zero stress condition (${\varepsilon_{33}}^F$) and zero strain condition (${\varepsilon_{33}}^B$).

The electrical properties of the sensor were determined with an admittance (capacitive) bridge circuit excited by a synthesized signal generator (Agilent N9310) in the range from 100 KHz to 90 MHz. The output signals from the bridge were captured by a fast digitizer (Agilent U2702, 0.5 Gs/s, 200 MHz) and processed with an FFT routine. The bridge was calibrated with measurements in the "open" condition and also with a reference capacitor (ceramic C0G dielectric, 47 pF). The low-loss reference capacitor was previously characterized with a vector network analyzer to ensure that its self-resonant frequency was over 250 MHz, well above the intended measurement range. The measurement concept is described in Ref. 5 and the details of the measurement method and the calibration procedures are given in Ref. 6. It must be stressed

a)Author to whom correspondence should be addressed. Electronic mail: mggonza@fi.uba.ar

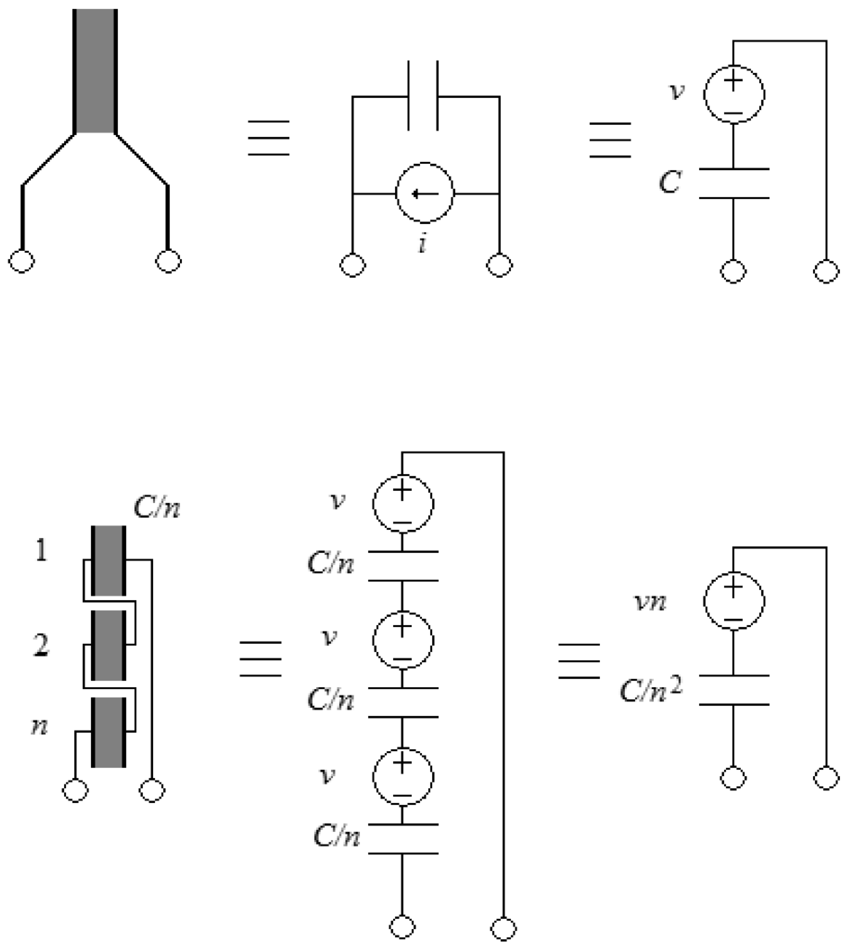

FIG. 1. Equivalent electric circuit.

TABLE I. Values at different frequencies of the electromechanical parameters of the PVDF film used in this work ($T = 300$ K).

	100 Hz	1 kHz	10 kHz	100 kHz	1 MHz	10 MHz
d_{33} (10^{-12} C/N)	−33.5 + j0.6	−31.7 + j1.4	−29.3 + j2.1	−25.3 + j4	−17.4 + j6.2	−7.6 + j5.7
s_{33} (10^{-9} m^2/N)	0.44 − j0.01	0.41 − j0.02	0.38 − j0.03	0.33 − j0.05	0.22 − j0.08	0.1 − j0.07
$\varepsilon_{33}{}^F$	11.2 + j0.19	11 + j0.18	10.7 + j0.36	9.9 + j0.81	8.2 + j1.35	6.1 + j1.25
$\varepsilon_{33}{}^B$	10.9 + j0.18	10.7 + j0.18	10.4 + j0.34	9.7 + j0.77	8.1 + j1.29	6 + j1.21

that, as indicated in these references, careful consideration must be given to the characterization of the coaxial cables used in the measurement setup. This is essential to correct the systematic errors in measurements at high frequencies, particularly above 1 MHz.

The mechanical impulse response was determined with the same setup of Ref. 7. A Nd:YAG laser with a second harmonic generator (Continuum Minilite I, 532 nm, 5 ns, 10 Hz) was used to generate a gaussian pressure signal on the silver paint layer that adheres the piezoelectric film to the BK7 glass substrate. To amplify the signal, a transimpedance amplifier (Femto HCA-100M-50K-C) was used. The amplifier characteristics were measured independently with a network analyzer at frequencies from 100 kHz to 200 MHz (Figure 2). The frequency response was fitted as a second order transfer with low-frequency gain 49.2 kV/A, natural angular frequency 628.3 M/s, and quality factor 0.34.

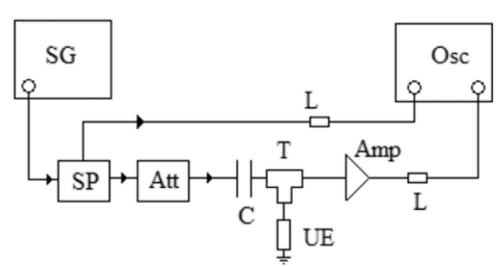

FIG. 2. SG: Agilent N9310 signal generator; Osc: Agilent U2702 oscilloscope; SP: 50 Ω splitter; Att: 20 dB Hewlett-Packard attenuator; C = 2.7 pF; T: T connector; UE: Unsegmented Electrode sensor; Amp: Transimpedance amplifier; L: 50 Ω load.

The amplifier output was digitized by an oscilloscope (Tektronix TDS 2024, 2 GS/s, 200 MHz) and processed on a personal computer. The oscilloscope trigger signal was

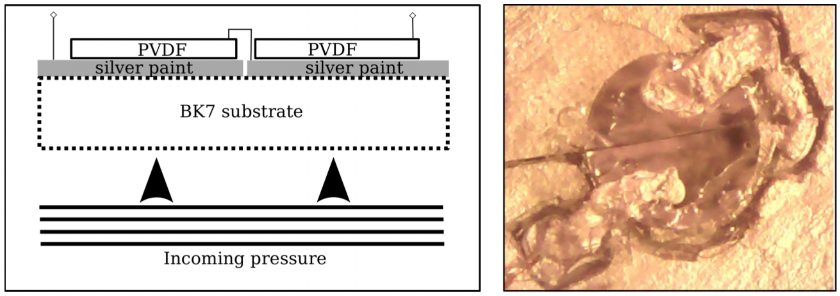

FIG. 3. Left: sensor schematic. Right: sensor prototype (back view).

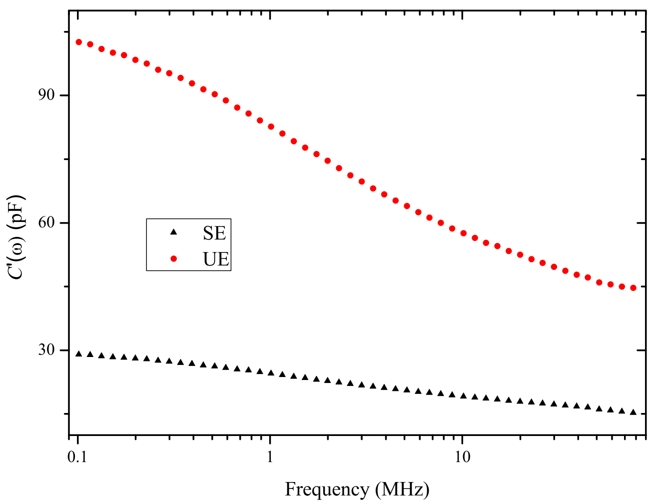

FIG. 4. Real part of the capacitance vs. frequency.

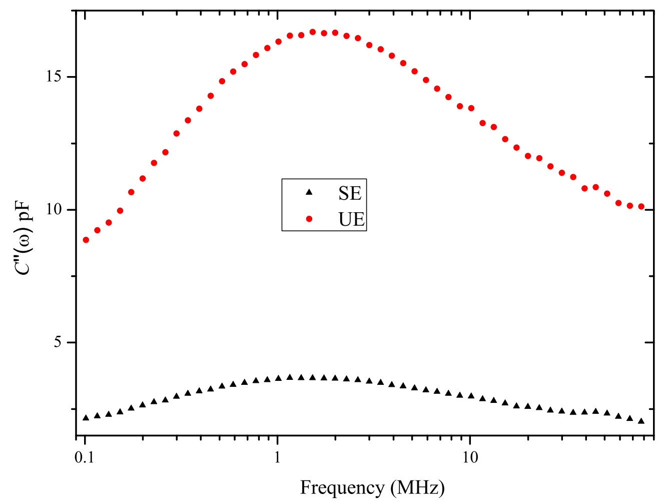

FIG. 5. Imaginary part of the capacitance vs. frequency.

obtained from the Q-Switch pulse. A diverging lens was used to uniformly illuminate the surface of the sensor.

The measured impulse response was analyzed using the model presented in Ref. 7, where the mechanical variables are considered as an acoustic transmission line and the electrical behavior by the quasi-static approximation. It is important to remark that, from the electrical point of view, the quasi-static description is still appropriate given the large difference between the velocities of propagation of the electrical and mechanical disturbances. The line parameters were calculated from the values of the material properties given in the Table I.

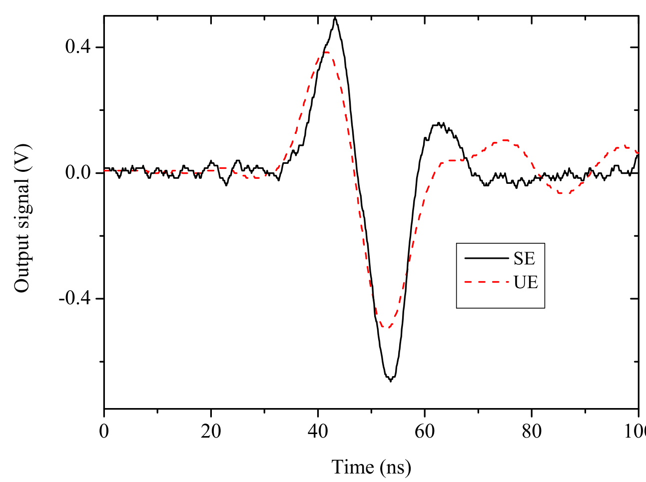

FIG. 6. Impulse response.

III. EXPERIMENTAL RESULTS

To test the idea, we built an SE with $N = 2$ sections. We employed a disk-shaped, piezoelectric thin film (diameter 6 mm) with the properties described in Sec. II and cut it across a diameter. We connected the sub-detectors with conductive silver paint. In addition, we built a reference, UE detector with the same dimensions. As a substrate, we resorted to BK7 glass blanks (Figure 3) and enclosed each detector in a brass shielding.

The simplest electrical equivalent model of the thin-film PVDF transducer is a current source in parallel with a lossy, frequency-dependent capacitor: $C(\omega) = C'(\omega) - jC''(\omega)$. Figures 4 and 5 show the real and imaginary parts of $C(\omega)$ for both the SE and UE detectors. The high frequency decrease in the real part and the peak in the imaginary part are originated by the β dielectric relaxation process, attributable to fluctuations of the dipolar moment of localized parts of the main polymer chain.[8] This relaxation process can be described by a Havriliak-Negami (HN) function.[9] Moreover, in Figure 5, it is possible to observe the first mechanical resonance (film thickness resonance) at about 40 MHz, as predicted by the acoustic transmission line model.

As expected, within the measured range, both the real and imaginary parts of $C(\omega)$ of the SE are about one-fourth of the value of the UE.

Figure 6 shows the impulse response of both sensors. Following the analysis of Ref. 7, it is expected that the signals should resemble the first derivative of the gaussian pressure pulse. However, the negative peak is slightly larger than the positive one because, even though the mechanical disturbance attenuates as it travels down the film, the reflected wave at the air-PVDF interface adds a small amount to the registered signal. The secondary peaks are associated with the wave reflected from the silver-glass interface.

The similarity between the two plots indicates that there are no significant differences between the mechanical responses of the SE and the UE.

IV. CONCLUSIONS

We show in this work that thin film piezoelectric sensors can be segmented and connected in series in order to reduce the electrical capacitance. In this way, the design of the wideband amplifier stage is simplified and the mechanical response is not altered. This is relevant for the applications of large area detectors where good directivity is required, such as optoacoustic tomography. In addition, it is possible to overcome the following trade-off. The thinner the film, the higher the first mechanical resonance and thus the upper frequency limit. However, the thinner the film, the higher the capacitance. With the segmented detector, it is possible to use a very thin film and make up for the increased capacitance by using the series connection.

ACKNOWLEDGMENTS

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