

Domain-Engineered Thin-Film LiNbO₃ Pyroelectric-Bicell Optical Detector

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Abstract—We have fabricated a bicell detector consisting of a single freestanding film of single-crystal lithium niobate (LiNbO₃) 10- μm thick, having two adjacent domains of opposite spontaneous polarization, and hence, two adjacent pyroelectric detector regions of equal and opposite sensitivity. The film was created by applying the process of crystal ion slicing and electric field poling (domain engineering) to a Z-cut LiNbO₃ wafer. The detector's noise equivalent power was $6 \text{ nW} \cdot \text{Hz}^{-1/2}$ at 16 Hz, and the ambient temperature-dependent variation of the detector's response near room temperature was $0.1\% \text{ K}^{-1}$. The acoustic noise sensitivity measured at 100 Hz was -24 dB relative to that of a single-domain detector.

Index Terms—Domain engineering, optical detector, pyroelectric detector, thin-film devices.

I. INTRODUCTION

DUE TO THEIR flat spectral response over a broad wavelength range from the ultraviolet up to $25 \mu\text{m}$ and room-temperature operation, pyroelectric materials remain a key choice for building transfer-standard detectors for radiometric applications, including those at telecommunication wavelengths. For practical purposes, however, it would be desirable to reduce the acoustic and ambient-temperature sensitivity of these detectors, and to produce large-area pyroelectric detectors with increased optical detectivity. In recent years, the process of domain engineering of ferroelectric crystals has been implemented for building position-sensing devices (illumination of multiple domains of a multidomain structure), or to reduce the acoustic sensitivity of radiometric sensors (illumination of a single domain of a multi-domain structure) [1], [2]. Separately, the process of crystal ion slicing (CIS) has been employed to create high-sensitivity single-crystal thin-film ferroelectric-pyroelectric detectors having a geometrical aspect ratio greater than $500:1$ [3]. By combining these two processes, we have fabricated a large-area thin-film pyroelectric detector of single-crystal lithium niobate (LiNbO₃) with high optical sensitivity, and reduced acoustic and ambient temperature sensitivity. Unlike other thin-film pyroelectric detectors typically used in position-sensing devices [4], the CIS pyroelectric-bicell

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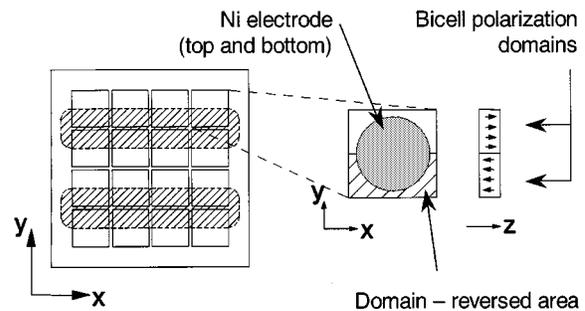


Fig. 1. Sixteen $4\text{-mm} \times 4\text{-mm}$ bicells were cut from the parent wafer following a single poling operation, prior to ion implantation. The orientation of the X and Y axes is arbitrary and is shown only to reference the crystal's Z axis.

detectors described here fully maintain the single-crystal properties of their bulk counterparts. These features are critical for fabrication of transfer-standard detectors for calibration of optical-fiber power meters used in optical telecommunication systems, as well as for characterization of laser and broadband sources in the infrared. In addition, due to their low thermal mass, domain-engineered thin-film detectors have the potential to serve as calibration standards for low-energy short-pulse measurement applications.

II. DETECTOR FABRICATION

The bicell pyroelectric detector was fabricated from a Z-cut LiNbO₃ parent wafer as shown in Fig. 1. Two pairs of 25-nm-thick nickel (Ni) poling electrodes, defined by a shadow mask, were deposited onto a $5.3 \times 5.3 \text{ mm}^2$ 250- μm -thick LiNbO₃ plate. The spontaneous polarization of those regions was reversed by applying a coercive field by means of a technique described by Meyers *et al.* [5]. Sixteen individual parent bicells were cut from the parent wafer and the Ni-poling electrodes were removed by a ferric chloride etch. The film material for the bicell pyroelectric detectors was then fabricated using the ion-slicing method described previously by Levy *et al.* [6]. To enable separation of a surface layer from the substrate, the parent bicells were ion implanted with He⁺ at 3.8 MeV to a total implant dose of $5 \times 10^{16} \text{ ions/cm}^2$ and then rapidly annealed at $300 \text{ }^\circ\text{C}$ for 20 s [7]. The implant side was encapsulated in black wax and then submerged in a solution of 5% hydrofluoric acid. After the film separation due to etching and removal of the encapsulation, the bicell films were annealed for six h at $450 \text{ }^\circ\text{C}$ in a flowing atmosphere of argon and oxygen. Finally, a 25-nm-thick Ni electrode was deposited over an area of 3 mm in diameter on both sides of the film. Each film was packaged as a

freestanding detector, so that the sensitivity and spatial uniformity at low frequencies (<10 kHz) would not be compromised by a heat-sink substrate [3]. The front surface of the film, encapsulated during the etch process, appeared specular to the naked eye, while the opposite side was nearly specular with some diffuse structure apparent due to etching.

The finished bicell detector was $10\ \mu\text{m}$ thick and 3 mm in diameter, with two symmetrical regions each having equal and opposite spontaneous polarization, and hence, relevant pyroelectric and piezoelectric coefficients of equal magnitude and opposite sign. The phase reversal in two adjacent detector regions of approximately equal area presents a basis for cancellation of the piezoelectric currents generated by ambient acoustic fluctuations.

III. EVALUATION AND DISCUSSION

We have evaluated the sensitivity, spatial uniformity, and temperature dependence to determine the performance of the bicell detector, and compared its measured properties with a comparable uniformly poled CIS LiNbO_3 detector (monocell).

The value of the noise equivalent power (NEP) was measured with an optical source consisting of a 0.31-mW mechanically chopped 1570-nm wavelength laser beam. The pyroelectric detector's output, both signal and noise, was measured with a 10^{-10} A/V current-mode preamplifier connected to a lock-in amplifier, referenced to the chopping frequency. The signal-to-noise ratio was calculated and averaged from 25 samples, resulting in a standard deviation of 8%. The value of the NEP was $6\ \text{nW/Hz}^{1/2}$ and $22\ \text{nW/Hz}^{1/2}$ at 16 and 100 Hz, respectively, consistent with the detector's frequency response.

To confirm the reduced acoustic sensitivity of the bicell, it was compared to the monocell at an acoustic frequency of 100 Hz, again with a current preamplifier and a lock-in amplifier but referenced to a sine-wave-driven loudspeaker. The acoustic sensitivity of the domain-engineered detector was 24 dB less than the monocell with a standard deviation of 1 dB for 60 samples acquired for each detector. This result was corroborated using a Fourier transform spectrum analyzer rather than a lock-in; however, the uncertainty of this measurement has not been fully evaluated.

The spatial uniformity was measured using a 0.3-mW 1570-nm laser diode focused at the detector plane, such that greater than 99.9% of the total beam power was within a radius of $50\ \mu\text{m}$ of the beam's centroid. The detector's current response was obtained, as before, with a lock-in amplifier and by modulating the optical input at 75 Hz. The laser was moved across the detector's aperture at $100\text{-}\mu\text{m}$ intervals in a plane parallel to the detector plane with a six-axis robotic arm. The detector signal was sampled and recorded at each interval and the data were normalized to the value of the highest response of any location on the detector. A surface map of this data is shown in Fig. 2. A cross section of Fig. 2 is shown in Fig. 3 to indicate several aspects of the detector's response in greater detail. The magnitude of the average response of the domain-reversed half of the bicell was -75% , while that for the other half, accompanied by a complete (180°) phase reversal across the domain boundary, was 90% . The decreased response of the

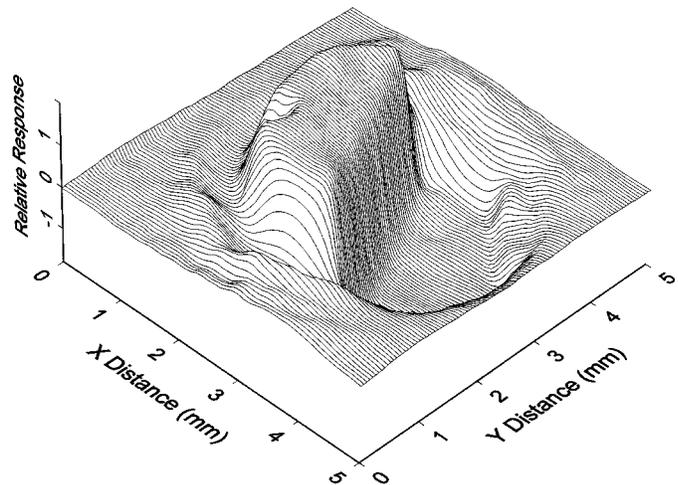


Fig. 2. Surface map of the bicell's spatial uniformity.

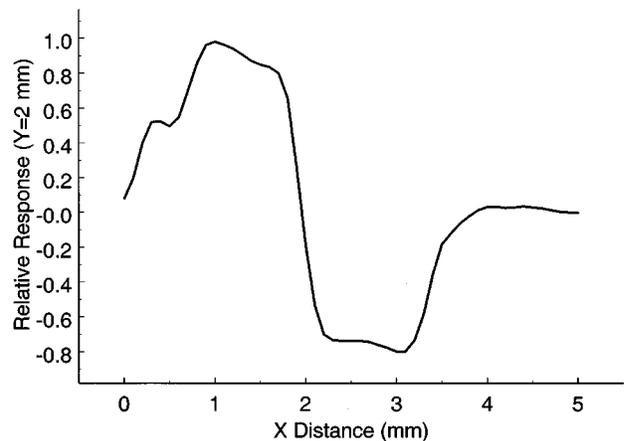


Fig. 3. Cross section of Fig. 2 at Y distance of 2 mm.

detector at an (X, Y) location of (1.5 mm, 2 mm) corresponds to the location of conducting epoxy on the back face, which acts as a heat sink at chopping speeds of less than 10 kHz [3].

The slope toward the midline of the bicell is due to variation of the crystal's thickness. The relative variation in the detector's thickness was measured with a mechanical-probe profilometer to verify the presence of a step at the domain boundary due to preferential etching of the $-Z$ domains. The difference in step height varied from ~ 140 nm at the film perimeter to ~ 90 nm at the film center, indicating a relative thinning toward the edge, as the outer area of the film has been exposed to the etchant longer than the inner area. We expect the detector's spatial uniformity to be a function of film thickness due to thermal diffusion at 75 Hz, because the crystal is sufficiently thin that the temperature of the back surface changes at nearly the same rate as the front [3]. However, the LiNbO_3 is sufficiently thin that we must also consider changes in optical absorption due to interference effects as a function of film thickness. For example, the optical absorption of a $10\text{-}\mu\text{m}$ (single-domain) LiNbO_3 film with 25-nm-thick Ni electrodes is 10% smaller relative to that for a $9.8\text{-}\mu\text{m}$ LiNbO_3 film. This difference in relative absorption due to variation in film thickness is in accordance with the observed detector spatial uniformity and our profilometry measurements.

It is important to note, however, that the effect of thickness variation on the bicell's spatial response can be greatly minimized by applying a high-efficiency coating such as gold black, which can convert more than 99% of incident optical radiation into thermal energy.

It has been reported earlier that domain-engineered pyro-electric detectors are less sensitive to fluctuations in ambient temperature as compared to single-domain detectors [1]. Thus, the thin-film detectors were evaluated by comparing the measured change of the bicell detector's response with that of a monocell detector over a range of operable temperatures between 22 °C and 34 °C. The change in the detector response of the bicell was 1.5% over the temperature range, while the monocell's response varied 4%. The measurement method was essentially that described by Chynoweth and recommended by Hanson, with the exception that no external field was used [8]. When the temperature dependence was measured, only a small portion of a uniformly poled area of the detector was illuminated.

The almost three-fold reduction of the detector's sensitivity to ambient temperature fluctuations is expected based on previous accounts; however, this phenomenon has not been fully understood [1], [9]. In the present case, we offer the following explanation. The pyroelectric signal consists of two terms arising from the primary and secondary pyroelectric effects. The first term is proportional to the current generated by the detector if the crystal were completely constrained and unable to expand. The second term exists when the crystal is free to deform and is proportional to the tensor product of the piezoelectric coefficients, the elastic stiffness, and the coefficient of thermal expansion. The bicell detector described here is only partially constrained and may be structurally modeled as a clamped circular plate with the addition of a domain boundary orthogonal to the detector plane. Therefore, we must consider both the primary and secondary effects. It has been shown that the macroscopic properties of the bicell detector, relevant to the secondary pyroelectric effect, are different from the volume average of the properties of the monocell [10]. If for example, the calculated value of the relevant piezoelectric coefficient p_{33} were lower for a bicell than for a uniformly poled crystal, we might conclude that the bicell detector's response would have a reduced dependence on thermally induced strain. However, the magnitude of p_{33} does not explain why the response of the two detectors changes at a different rate. Compared to the monocell detector, the presence of the domain boundary in the bicell detector increases the structural stiffness, while the magnitude and distribution of strain vary at each equilibrium temperature at which the detectors are evaluated. Consequently, the significant difference between the two cases is that structural stiffening reduces the magnitude of piezoelectric current generated due to thermal strain. Considering the subtleties of physically mounting the detector

film, we have not tried to quantitatively predict the temperature dependence. In general, relative to single-domain detectors, a bicell detector will typically be less sensitive to changes in ambient temperature and the behavior must be evaluated on a case-by-case basis.

IV. CONCLUSION

We have demonstrated that it is possible to build a thin-film single-crystal LiNbO₃ pyroelectric detector and to use the process of domain engineering to decrease the acoustic and ambient temperature sensitivity without loss of optical sensitivity. These are two major steps toward building a practical large area and spatially uniform domain-engineered pyroelectric detector with nanowatt sensitivity and reduced dependence on ambient temperature. A remaining challenge is to incorporate a thermal coating with a high absorptive efficiency such as gold black, while sustaining the advantages we have described.

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