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We report the pyroelectric response of c-axis oriented, undoped, wurtzite, aluminum nitride reactively sputtered onto polished silicon wafers. The voltage between a metallic contact on the AlN surface and the n-type doped silicon substrate was monitored during pulsed infrared, radiant heating. From analysis of the data, a pyroelectric voltage coefficient, \( P_v \), in excess of \( 0.5 \times 10^6 \) V/m/K was extracted for films in the 600 to 2500 Å thickness range.

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The modeling program used for this project was E-Z Thermal available from GK Solutions, 1606 Slate Run Circle NE, Canton, OH 44721, (330) 499-3410.

Experimental

In this study we measured the PE voltage response of thin films of AlN prepared by dc reactive sputtering of aluminum in a 3 × 10^{-3} Torr ammonia atmosphere. The power density at the target was ~5 W/cm². The substrates were 0.1 Ω-cm, n-type, polished silicon wafers with (111) orientation. The substrates were rinsed in hot acetone, methanol, and DI water, etched in electronic grade buffered HF acid, rinsed in DI water, and dried in a zero grade nitrogen stream. Prior to the sputter deposition, the substrates were heated in situ above 200°C and cooled below 50°C while the chamber was at or below 5 × 10^{-8} Torr. From X-ray diffraction (XRD) patterns the AlN films were determined to be highly disordered with a broad peak corresponding to the d-spacing of the (0002) reflection, which is oriented normal to the substrate surface. Neither the XRD patterns nor ESCA profiles of the AlN layer showed any sign of free aluminum, implying that the films were essentially stoichiometric. Hot probe measurements showed the films to be semi-insulating to slightly p-type with typical through-film resistance of 25 MΩ/μm for 1 cm² of area. The thickness of films varied from 540 to 2500 Å ± 50 Å controlled by sputtering time. Subsequent to the AlN deposition, a 100-200 Å layer of NiCr was applied, by radio-frequency (RF) magnetron sputtering in argon, to act as both a contact to the AlN and to increase absorbance at IR wavelengths. The n-type silicon substrate was used as the back contact. To measure the PE response, a broadband IR source was focused onto the specimen after passing through a vane chopper. An undoped silicon wafer, etched and polished on both sides, was interposed between the source and the specimen to remove any light of frequency above the band gap of silicon and, thereby, suppress photovoltaic responses associated with substrate absorption.

Results and Discussion

The voltage response to the chopped IR source is shown in Fig. 1 for one of the specimens. As expected for a pyroelectric material, the AlN film responded to the time rate of change of temperature (dT/dt) rather than to the absolute value of temperature difference per sec. A first estimate of response time can be obtained from the exponential decay part of the trace. The relaxation after the initial rise was fitted to an exponential as shown in Fig. 2, from which a 1/e response time of 0.013 s is calculated. By assuming a rise in temperature linearly proportional to the rate of energy input and an exponential fall in temperature proportional to the thermal conductivity of the AlN and Si substrate, the time to reach the maximum rate of temperature change is 0.011 s, which is close to the 0.0067 s to reach the maximum output voltage. The relationship used to determine \( P_v \) is (see, for example, Ref. 8, p. 94)

\[
\Delta V \Delta t = P_v h \Delta T / \Delta t
\]

where \( V \) is the measured voltage, \( T \) (K) is the calculated temperature, \( t \) (s) is the time, and \( h \) is the layer thickness; 600 Å for this specimen.

Both \( \Delta V / \Delta t \) and \( \Delta T / \Delta t \) are obtained from analysis of the Fig. 2, and a pyroelectric voltage coefficient of \( P_v = 0.51-0.69 \times 10^6 \) V/m/K was extracted for this particular 600 Å thick AlN layer. The range for \( P_v \) depends on how one chooses the time range for calculating \( \Delta V / \Delta t \) and \( \Delta T / \Delta t \). The thermal responses, shown on the figure, were constructed using material properties values from the literature and a commercial finite difference heat flow calculation program. In Fig. 3 the response to a shuttered IR pulse is shown for a complete cycle. In that figure the peak voltage for the 2500 Å thick specimen is 71.6 mV. There is a residual output, \( V_0 \) = 7.5 mV,
and the incident power density was 3.1 6 \text{j} of Figure 2.

The data from the positive response half cycle of Fig. 1 measured an AlN PE charge coefficient of $P_Q$ et al., measured PE values are not expected for these compounds. Indeed, Fuflyigin et al. measured AlN and GaN, however, are quite high and so such large and greater than that thus far reported for GaN. The crystal symmetry of both AlN and GaN, however, are quite high and so such large PE values are not expected for these compounds. Indeed, Fuflyigin et al. measured an AlN PE charge coefficient of $P_Q = 6-8 \mu C/\text{m}^2$, which is at least two orders lower than typical for commercial PE materials. Assuming a relative dielectric constant for AlN of $\kappa = 8.5$, the $P_Q$ above converts to a PE voltage coefficient.

During the illuminated part of the cycle which is due to the finite continuous heat flux through the film because of the difference in absolute temperature of its two sides.\textsuperscript{8}

In summary, AlN appears to have a PE voltage response comparable to values found for materials used for commercial detectors\textsuperscript{8} and greater than that thus far reported for GaN. The crystal symmetry of both AlN and GaN, however, are quite high and so such large PE values are not expected for these compounds. Indeed, Fuflyigin et al. measured an AlN PE charge coefficient of $P_Q = 6-8 \mu C/\text{m}^2$, which is at least two orders lower than typical for commercial PE materials. Assuming a relative dielectric constant for AlN of $\kappa = 8.5$, the $P_Q$ above converts to a PE voltage coefficient.

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