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MEASUREMENTS ON PVF$_2$ POLYMER TRANSDUCERS

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INTRODUCTION

Polyvinylidene fluoride (PVF$_2$) is a polymer which can be extruded into very thin sheets and polarised to form piezoelectric transducers. The material is transparent, flexible, lightweight, cheap, and resistant to mechanical and thermal shock and to chemical attack. Electodes can be easily vapour-deposited onto its surface in any desired configuration.

PVF$_2$ has been used in microphones, loudspeakers and switches, but although its characteristic impedance is very close to that of water, thereby ensuring good matching, its possible applications as an underwater transducer have not been exploited.

At Loughborough we are just beginning a research project to study the potential of this material for underwater devices, particularly ultrasound receivers. Our studies so far have included some basic measurements of material parameters, such as the piezoelectric constants d_{33} and g_{33} which describe transmitting and receiving performance in the thickness direction. Our ultimate expectation is to construct a multielement array for acoustic imaging.

SOME PROPERTIES OF PVF_2

Polyvinylidene fluoride is primarily manufactured for use as a packing and insulating material and for handling radioactive and corrosive chemicals. But since 1968, when the first details of its piezoelectric properties were published in Japan, its application as a transducer material has become of great interest. It is readily obtainable in thin sheets down to 6 microns thick, and transducers can be made with flat responses as high as 500 MHz.

The material exists in two basic forms, referred to as phase I (β-form) and phase II (α-form). They can exist separately or together, and their presence can be determined by infra-red absorption techniques. Although both forms have dipole moments in their molecular chains (β has the larger moment), neither has a resultant macromolecular dipole moment unless polarised in a D.C. electric field. Both forms of PVF_2 can be established when the raw material (pellets) is extruded during the manufacture of thin sheets. If thick sheets resulting from injection or compression moulding are available, then typically the α-form is obtained if the material is stretched by 400% at 160°C (near the melting point), and the β-form if it is stretched by 400% at 50 - 90°C.

The precise mechanisms of dipole orientation in PVF_2 under the influence of poling fields are not fully understood, and the reader is spared any further confusion about it here. It is sufficient to say that the material is both piezoelectric and pyroelectric, and therefore develops a surface potential difference due to either pressure or temperature fields.

Theoretically, the equivalent electrical circuit of PVF_2 is the same as for any piezoelectric material, namely an LCR series circuit (motional impedance arm) in parallel with a capacitance C_0 (electrical impedance arm). But because of the low mass of thin PVF_2 sheets the L component of the motional arm can reasonably be neglected over the flat response part of the frequency spectrum. Mechanically, therefore, the material is predominantly stiffness-controlled.

TRANSDUCER CONSTRUCTION

Electroding of PVF$_2$ transducers is usually effected by vapour deposition of a metal in a vacuum chamber, and for permanent adhesion the metal must be bonded chemically to the polymer surface. This necessitates the use of reactive metals such as aluminium, nickel, chromium and nichrome. Electrodes with simple geometry such as circles or squares are readily made by using a suitable mask; but if an array of very small electrodes is required it is better to use photolithographic techniques.

When provided with electrodes PVF$_2$ can be permanently polarised by the application of a high D.C. electric field. Poling fields can be as high as 2 - 3 MV cm^{-1} and are limited only by dielectric breakdown of the material. Generally speaking, the receiving sensitivity of a PVF$_2$ transducer, for a particular poling temperature, increases linearly as the magnitude of its original poling field. It also increases linearly with temperature for a given poling field. These dependencies are illustrated in Figures 1 and 2 for a number of identical 25-micron thick devices of 20 mm diameter. The poling voltages ranged from 600V to 1kV, corresponding to electric fields of 240 to 400 kV cm^{-1}, and the temperatures ranged from 60°C to 105°C. Subsequent measurements for fields up to 1.65 MV cm^{-1} have substantiated these observations of linear dependency. The vertical axes of Figures 1 and 2 are relative voltage outputs of the various transducers, all situated (separately) at the same distance from a conventional source transducer.

There is also a non-linear time dependency, and our experiments have indicated that to make a transducer with maximum sensitivity - for a given temperature and electric field - a minimum of 30 minutes poling time is required.

MEASUREMENTS

One of our earliest measurements was to compare the receiving sensitivity of a 25- micron thick PVF$_2$ transducer with a conventional PZT-4 transducer of the same area, when situated (separately) at the same location in the far field of an acoustic source, simply by monitoring the two output voltages. With the PZT-4 transducer receiving at its fundamental resonance frequency of 2 MHz, it was superior to the flat-response PVF_2 transducer by 50 dB. When receiving off-resonance, at 4 MHz, the PZT-4 transducer was 30 dB better. No measurements were made with the PVF_2 transducer receiving at a thickness resonance frequency because it was impractical to drive the available source above a few MHz.

However, we have the facilities to make a PVF_2 transducer of sufficient thickness to have a fundamental resonance frequency - and hence much improved response - in the low radio frequency region. The technique is to form the basic shape required by injection or compression moulding of the raw material then stretch it by some 400% in a tensile test machine. For a 1mm thick transducer, a poling field of up to 500 kV cm^{-1} can be applied.

The most useful parameters for determining the response of PVF_2 in its thickness (or "3") direction - appropriate for underwater applications - are the piezoelectric constants g_{33} and d_{33}, given as

$$S_3 = d_{33} E_3 \qquad (1)$$

$$E_3 = -g_{33} T_3 \qquad (2)$$

where d_{33} relates the elastic strain S_3 caused by an electric field E_3 (inverse effect) and g_{33} relates the electric field established by a compressive stress T_3 (direct effect). By re-writing (1) as

$$\delta t_3 = d_{33} V_3 \qquad (3)$$

the formula becomes independent of thickness. It is clear that d_{33} can be obtained by measuring the change of thickness δt_3 due to an applied D.C. voltage V_3. In this work 300V was applied and δt_3 was measured on a "Talystep" machine to an accuracy of better than 4 x 10^{-3} mm. Values of d_{33} up to 500 pC N^{-1} have been obtained, which is well above the quoted value of 289 pC N^{-1} for PZT-4 and 152 pC N^{-1} for PZT-2. However, the measured values were found to vary from point to point across the transducer electrodes (being maximum at the periphery) and the average value for d_{33} was generally an order of magnitude less than the maximum value.

The g_{33} constant has not yet been measured directly, but we have devised a system for doing it. Basically, a uniform stress is applied to the transducer surfaces by means of air pressure and the output voltage developed across the device is monitored. Taking the dielectric constant (K) into account, an estimation of g_{33} can be obtained from

$$d_{33}/g_{33} = \epsilon^T_{33} = K\epsilon_o \qquad (4)$$

Here ϵ^T_{33} is the absolute dielectric constant measured with $T_3 = 0$, and ϵ_o is the permittivity of free space (8.85×10^{-12} farad metre^{-1}). Thus for an average value of 50 pC N^{-1} for d_{33} and a measured value of 12 for K, g_{33} is about 0.5 VmN^{-1}. Comparing this figure with the quoted value of g_{33} (0.026 VmN^{-1}) for PZT-4, it is apparent that PVF_2 could make a good receiver.

CONCLUSIONS

At Loughborough we have only just begun to appreciate the complexities of the behaviour of PVF_2. However, we have made many transducers under different conditions, and have measured some of their important parameters.

A series of experiments is currently being undertaken to establish the precise variation of d_{33} and g_{33} with temperature, and to relate these to other piezoelectric, electric and elastic constants. This should fill an important gap in the literature because thickness vibration of PVF_2 has been little studied so far. There are many possible underwater applications of the material, not the least because of its close acoustic matching to water. Thus, by making use of this information the response of practical underwater transducers and arrays can be better assessed.

ACKNOWLEDGEMENTS

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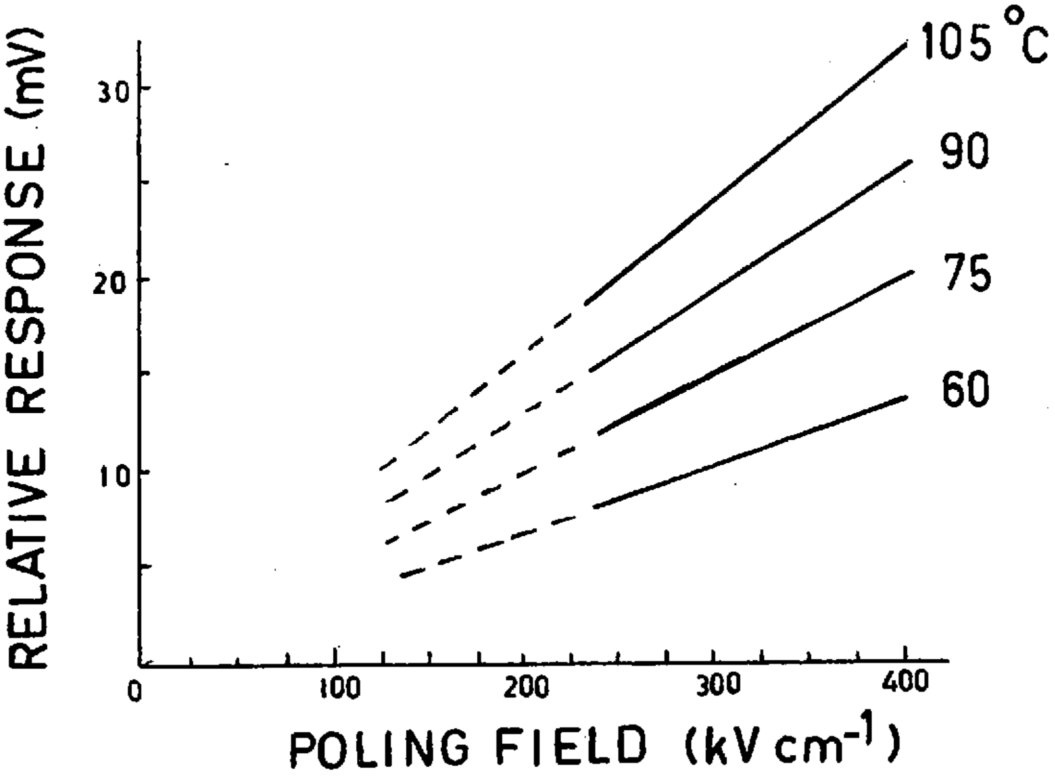

FIGURE 1

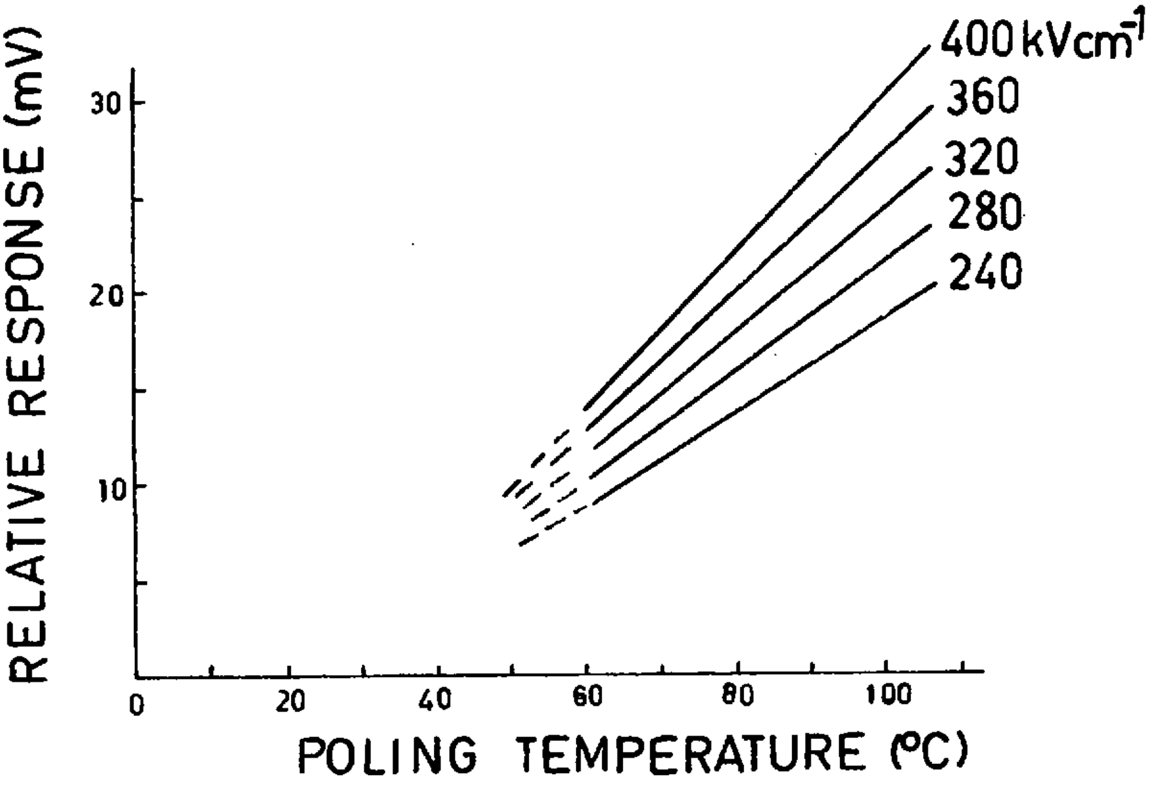

FIGURE 2