Appendix 1

Explanation of piezoelectric effect

The first explanation of the origin of the piezoelectric effect in terms of molecular structure was given by Lord Kelvin soon after the Curies' original discovery (Heising, 1946). Although the structure assumed by Kelvin has since been proved incorrect by X-ray crystallography, his explanation remains useful in a qualitative sense.

Figure A1.1 shows an arrangement of positive and negative ions which can serve as a crude model of the unit cell of a quartz crystal in the plane normal to the optic axis. The six ions are located at the corners of a regular hexagon. Assuming that the ions have charges $+q$ and $-q$, the net charge in the unit cell is zero. Moreover, because of the alternate arrangement of the positive and negative ions, the net dipole moment is also zero.

If now it is supposed that during a deformation of the crystal caused by the application of external stresses, the mutual forces acting between the ions in

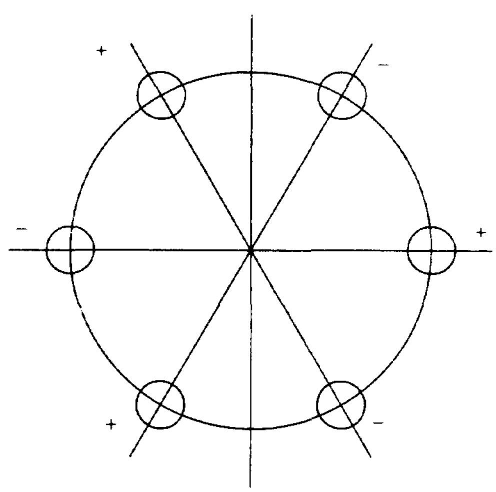

Fig. A1.1 Model of quartz 'molecule'.

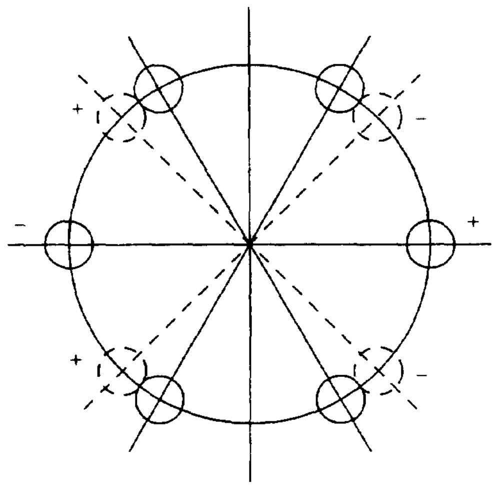

Fig. A1.2 Vertical compressional strain.

the cell are such as to maintain both the distance apart of opposite pairs of ions, and also their collinearity with the cell centre, then the deformation of the unit cell can be described in terms of the rotations of the lines joining the opposite pairs of ions. Figure A1.2 illustrates the case of a compression in the vertical direction. The ion pair in the horizontal direction is unaltered, but the remaining two ion pairs are rotated towards the horizontal. Clearly the centre of gravity of the positive ions is shifted towards the left, whereas that of the negative ions is shifted towards the right, the combined effect being to produce a non-zero dipole moment in the horizontal direction.

The reverse situation of a tensile stress in the vertical direction again leaves the horizontal ion pair unchanged but rotates the other two pairs away from the horizontal, producing a dipole moment oppositely directed to that produced by compression. Assuming a homogeneous strain, summing the dipole moments of all the unit cells throughout the material therefore results in an electrical polarization that reverses with the strain, that is, *piezoelectricity*. In this simple model, the horizontal direction lies along an *electric axis*. By inspection, there are three such axes, so that to this extent the model reflects the trigonal symmetry of quartz.

The same model can be used to demonstrate the production of electrical polarization by longitudinal strains in the horizontal direction, and also by shear strains in the plane of the paper. In the former case, the polarization is again along the horizontal axis, but a shear strain produces a polarization along the vertical axis. The details are however hardly relevant in practice since the actual structure of quartz is considerably more complicated than suggested here (cf. Vigoreux and Booth, 1950; Brice, 1985).