5 Electrical processing

5.1 CLEANING AND ETCHING

During the optical processing stages, crystal blanks are subject to a wide variety of soils and contaminants, all of which must be removed before the following process stages. In addition, by the nature of the lapping process, however fine an abrasive is used the surface of a lapped blank would still show on examination under sufficiently high magnification a fine structure of minute irregularities. These would include myriads of fine cracks and fissures, accompanied by occasional deeper scratches from abrasive particles with larger than average diameter, from dust particles, or from other foreign matter. Even in the case of (mechanically) polished blanks, it seems probable that a damaged layer from previous lapping stages still exists under the polished surface.

This lack of surface perfection has the immediate consequence of degrading the Q of the resonator, with the depth of the surface damage compared to the acoustic wavelength at the operating frequency giving some idea of the degree of degradation. Over a period of time, a less immediately obvious consequence of surface imperfections shows itself in a rapid upward drift of the resonator frequency caused by the physical loss of material from the resonator surfaces. This is the result of small particles of quartz having been loosened in the lapping process and subsequently separating completely from the main body of the material. To prevent this ageing it is necessary to remove any such loose particles by *etching* away the surface layers of the blank to obtain a more stable surface. This etching process at the same time improves the resonator Q by reducing acoustic losses at the surfaces.

The amount of material removed in the etching process is usually related by rule of thumb to the size of the abrasive used in the final lapping stage. However, in recent developments the application of the etching technique has been extended so that the process of *deep etching* or *chemical polishing* has become an alternative to the traditional mechanical polishing procedures. In chemical polishing the amount of material removed is one to two orders of magnitude more than in conventional etching, and chemically polished blanks are claimed to have Q factors as good as or better than mechanically polished units, and also to be mechanically more robust. Deep etching does however make more stringent demands on raw material quality, since the presence of certain defects can lead to deep etch pits and in some extreme cases to etch channels extending throughout the thickness of the blank.

Various etchants have been proposed but the most regularly used have been aqueous solutions of ammonium bifluoride or hydrofluoric acid. Most often these solutions are used hot to speed up the process, and in all cases the blanks need to be thoroughly rinsed to remove all traces of etchant before being passed on to the next processing stage. For the etching to proceed in a uniform manner the blanks must be thoroughly cleaned beforehand, and it is usual to integrate the cleaning and etching procedures into one sequence of operations.

Different manufacturers each have their own preferences, but a typical clean and etch sequence would include the following steps:

(1) Load blanks into cleaning jigs fabricated from stainless steel or other inert material. The jigs should be so designed that the maximum blank area is exposed to the cleaning process.
(2) Ultrasonic wash in any one of several alternative solutions or solvents, including detergents, alcohols, acetone, trichloroethylene, and acidic or alkaline baths. Sometimes a sequence of washes may be used.
(3) Thoroughly rinse blanks in deionized water.
(4) Etch in saturated ammonium bifluoride solution.
(5) Thoroughly rinse off all traces of etchant.
(6) Dry blanks, using any one of several alternative techniques such as spin drying, hot air blowers, or chemical displacement methods. The latter include simple procedures involving successive alcohol and acetone rinses followed by blow drying, and more sophisticated techniques using proprietary equipment based on blends of trichlorotrifluorethane.

However elaborate the washing sequence used, it seems impossible to remove all traces of contaminants by conventional methods. In recent years new techniques have been introduced to complement the traditional procedures, with the most effective appearing to be the exposure of the blanks to intense ultraviolet radiation. In the presence of oxygen, the UV radiation generates ozone, which is critical to the effectiveness of the cleaning method, hence the usual term *UV-ozone* cleaning (Vig, 1971, 1975). When used, this step is carried out after a conventional wash sequence and immediately before the deposition of electrodes.

5.2 BASE-PLATING

All resonators require some form of electrode structure. In early devices *air-gap* electrodes were used, consisting of metal plates separated from the surfaces of the resonator by a small gap. Later, electrodes deposited directly on the quartz surfaces by vacuum deposition became the universally accepted standard, and the overwhelming majority of currently produced crystal units still use this technique. Nevertheless, for resonators of the very highest precision and stability, air-gap electrodes are once more being used to avoid the instabilities associated with electrode stresses, so that the wheel has come full circle for these devices (Besson, 1976).

In the conventional approach using vacuum deposition, the shape of the electrodes is usually defined by using photo-etched plating masks. These are commonly used in a 'sandwich' arrangement of three layers held in a rigid frame to allow ease of handling. The sandwich consists of a mask to define the electrodes on one face, a spacer with nests in which to locate the crystal blanks, and a second mask to define the electrodes on the opposite face. The material used to fabricate the masks is generally stainless steel. After loading the crystal blanks into the masks, with each mask generally holding a large number of blanks, several masks are loaded into carriers in a vacuum chamber. Depending upon the design of the unit, provision is usually made for the carriers to rotate around the filaments during the plating operation so as to ensure uniform plating from blank to blank and mask to mask. Also it is usual to arrange for the masks to be automatically turned over on completion of plating on the first side of the blanks, so that the second side may be plated without breaking the vacuum in the system. Figure 5.1 shows the interior of a typical base-plating machine.

A high vacuum is necessary in the chamber to ensure the quality of the deposited film. This can be attained by using various different pumping systems, including oil diffusion pumps, turbomolecular pumps, ionization pumps, and cryogenic pumps. Diffusion pumps have been widely used in the past, but the modern trend is towards the use of cryogenic pumps, largely because of their ease of use and their inherent cleanliness.

The most commonly used electrode materials are silver, gold and aluminium, with copper having been used in some special applications. It is common to use a thin layer of chrome under silver or gold electrodes in order to improve the adhesion of the electrodes to the quartz, but this has the disadvantage of increasing the stresses in the electrodes and thereby providing additional sources of long-term instability. The electrode materials can be deposited either by sputtering or by evaporation; the latter being most popular. The thickness of material deposited is controlled by detecting the change in frequency of a monitor crystal exposed to the evaporant, the whole plating cycle usually being fully automated.

5.3 MOUNTING AND BONDING

The basic requirements in mounting crystal resonators are that the crystal be provided with mechanical support, with protection from adverse environ-

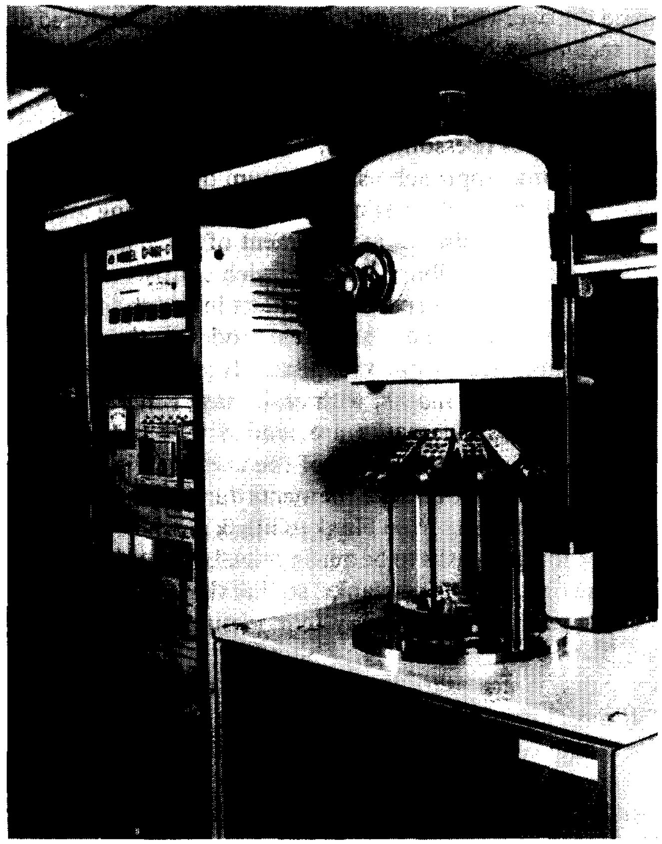

Fig. 5.1 Base plater.

mental effects (humidity, corrosive atmospheres, airborne contaminants, etc), and with some means of electrical connection to the driving circuit. At the same time, the mounting structure should impose minimal stresses on the resonator and minimize the damping of the mechanical resonance (Ward, 1983). The vast majority of medium to high precision resonators produced are packaged in hermetically sealed metal, glass or ceramic enclosures, with plastic occasionally being used in low cost, low precision applications. The metal enclosures can be further subdivided into solder seal, resistance weld and cold weld types, the subdivision being made according to the technique used to seal the cover of the enclosure to the header or base.

Figure 5.2 shows the structure of typical solder seal, resistance weld, and cold weld bases. In the solder seal and cold weld cases, the lead throughs are brought through the header by matched glass-to-metal seals, whereas in the resistance weld case the seal is of the compression type. In all cases the actual

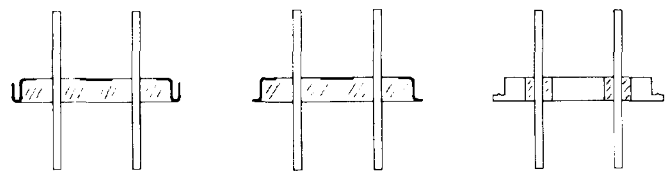

Fig. 5.2 Typical crystal headers.

mounting structure is typically welded to the lead throughs and can be chosen independently of the sealing method. Many different types of mount have been used over the years, and some of the most common are shown in Fig. 5.3. The choice of mount is largely determined by mechanical considerations, with rugged, stiff mounts being required to support blanks likely to be subjected to high shock levels, and more compliant mounts being required to minimize stresses on the crystal due to the mount itself. For large, low frequency blanks the problem of providing sufficient mechanical support without at the same time imposing undue stresses on the blank is particularly difficult, whereas on the other hand at higher frequencies the manufacturer has a relatively wide choice of satisfactory mount systems.

Whatever mount is chosen, the blank has to be secured in place with some form of adhesive, which must provide both mechanical strength and resilience and also be electrically conductive. The most commonly used are silver loaded epoxy resins or silver loaded polyimide pastes, the latter being more useful for higher temperature applications. The paste or resin is usually applied with a syringe or needle, and invariably requires to be cured at an elevated temperature before further processing. It is important that the paste does not out-gas appreciably during the curing cycle and so contaminate the crystal, and also important that the paste should not contain any chemical that will attack the electrode material and cause open-circuits. The latter can also be caused by paste that shrinks on curing. Figure 5.4 shows a selection of mounted and bonded blanks.

5.4 ADJUSTING TO FREQUENCY

After the final lapping stage, the tolerance on the blank frequency is of the order of 0.1%. After etching, the blank frequency is typically left higher than the desired nominal frequency by an amount of the order of 1% of the nominal frequency, allowing for the frequency to be brought down to nominal by the mass loading effect of the electrodes. The total amount by which the frequency is to be lowered in the base-plating and frequency

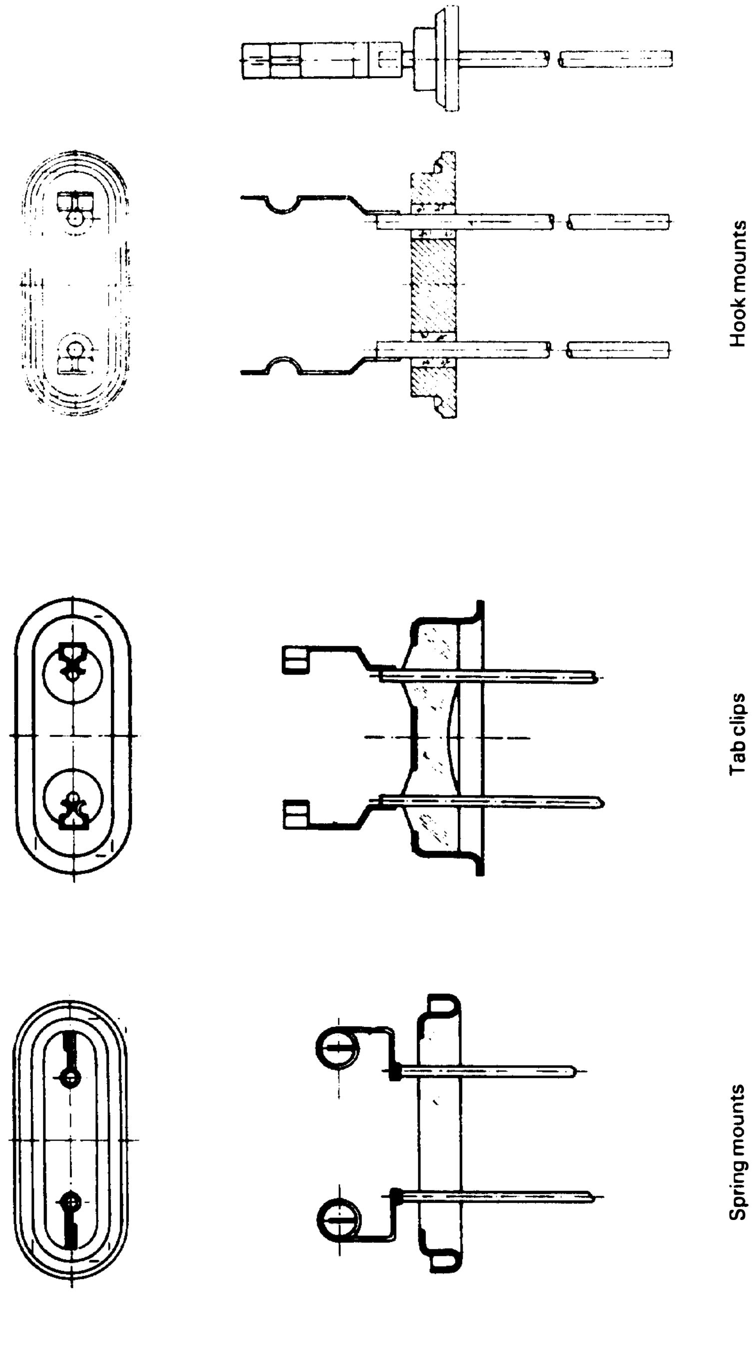

Fig. 5.3 Crystal mounts.

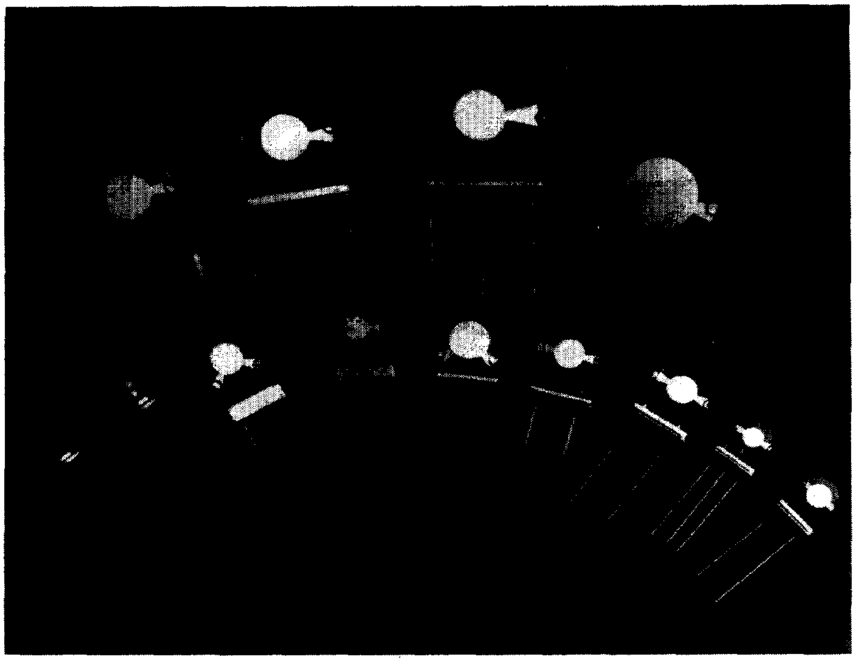

Fig. 5.4 Mounted crystal units.

adjusting processes is termed the *plateback* and is a key design factor. The final frequency tolerance required in the finished resonator is usually of the order of 10^{-5} or 10 ppm, that is two orders of magnitude tighter than the typical blank frequency tolerance after lapping and etching. Thus, although it would be very advantageous if the base-plating process were sufficiently accurately controlled to be able to plate to the nominal frequency, it is clear that the blank tolerances are generally too wide to allow this. Consequently, the objective in base-plating is to achieve a plateback of perhaps 80% of the total required, leaving the final frequency adjustment of the blanks to a later stage.

If this approach is followed, the crystal units after base-plating and mounting and bonding will be functional resonators with a frequency up to approximately 0.2% or 2000 ppm away from nominal. Each unit is then individually adjusted by evaporating small amounts of electrode material on to the resonator surfaces while observing the resonator frequency as measured by a suitable test set. Figure 5.5 shows an example of equipment designed for the automatic adjustment of a number of crystal units. The units are fitted with plating masks to limit the area to be plated to the central region of the base-plated electrodes, and then loaded into a carousel in a vacuum chamber. The chamber is evacuated and a stepping motor advances the carousel so that each crystal in turn is brought into the adjusting position. In this position the

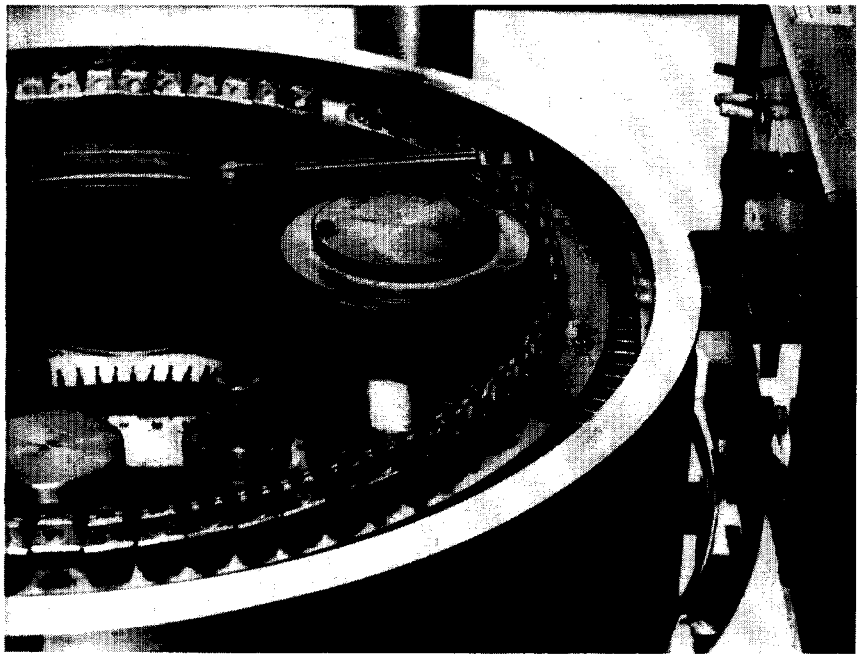

Fig. 5.5 Automatic adjuster.

crystal is situated between two filaments and also linked in to a frequency measuring system. The crystal frequency is measured and compared to a preset target frequency. Assuming that the measured frequency is above the target frequency, silver is evaporated from the filaments on to the crystal, bringing down the frequency by the mass loading effect. The system monitors the crystal frequency, and interposes shutters between the crystal and the filaments when the target frequency is reached.

An alternative to this procedure is known as *direct plating*, and omits the base-plating stage altogether. In direct plating the crystal blanks are cleaned and etched, and then passed straight to the mounting and bonding operation. At this stage of course the crystals have no electrodes and so are not functional, but are nevertheless loaded into an equipment similar to that described above. The key difference now is that the plating masks used must define the full electrode pattern, including the electrode 'tails' which provide electrical connection to the mounts. As each crystal in turn is indexed into the adjusting position, the filaments are first of all switched on for a set time period to deposit sufficient electrode material for the film to become conducting and for the crystal to start operating. Once the crystal begins to oscillate, then the frequency can be monitored and the process continues as before.

Direct plating has some significant advantages in small-scale production and also in regard to the superior control of the motional parameters of the crystal unit that it affords. There are also corresponding disadvantages relating to large volume production, and some doubts concerning the precision of the adjustment process related to the observed drift in resonator frequencies after the completion of the process.

5.5 SEALING

As already mentioned in Section 5.3, apart from low cost, low precision units, the majority of resonators produced, are packaged in hermetically sealed metal, glass or ceramic packages. Glass holders can be of the tubular type, similar to thermionic valve enclosures, or more commonly of identical outline dimensions to the standard metal holders. The headers for these latter type of glass units generally contain a metal ring which in the sealing process is heated by RF induction techniques until the surrounding glass melts and fuses with the glass of the cover. The process is very suitable for use with high temperature, high vacuum bake-outs immediately before sealing, and can produce units with extremely good ageing rates, but in volume production is difficult to control and the pieceparts are relatively expensive. The recently introduced ceramic packages (Peters, 1976) require specialized sealing processes and are not yet in wide commercial use, so consequently the various types of metal enclosure are those most widely used at present.

Solder seal holders are, as the name implies, sealed by soldering the cover to the base or header. This is the oldest method of sealing metal holders, and suffers from the major disadvantage of contamination of the crystal by the flux used in the soldering operation. Solder sealing has consequently largely been replaced by resistance welding, which besides being free from flux problems, also lends itself to automation. Resistance welding depends on the fusing of the material of cover and header caused by the passage of a heavy current through the flanges of the pieceparts, which are held under moderate pressure in a dieset. Figure 5.6 shows a typical welder. The welding current can be either AC, or a DC pulse obtained by the discharge of a capacitor bank. The welding operation is normally carried out in a glovebox in a dry, inert atmosphere, the crystal units being brought in to the system via a vacuum oven and removed via an air-lock.

Cold welding is the term used to describe welds obtained by applying extreme pressure to the mating surfaces in such a way that any contaminated or oxidized surface layers are pushed aside to allow intimate contact between the atomically clean metals. This process, which requires precision tooling in order to ensure a uniform seal all around the flanges of the base and cover, has the advantages of not requiring any application of heat and of being

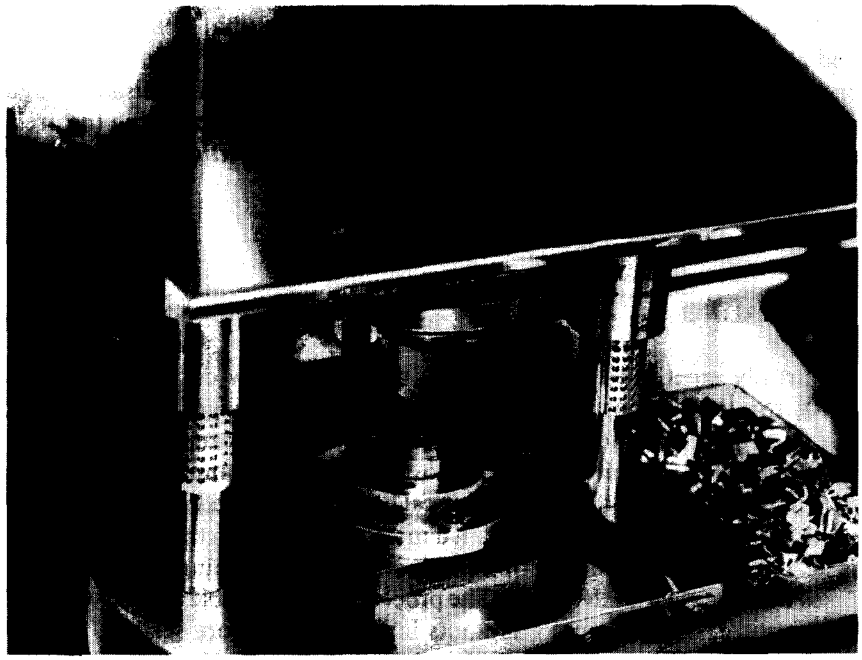

Fig. 5.6 Resistance welder.

easily built in to a high vacuum system. Hence cold weld units can be sealed under high vacuum or backfilled with inert gases without difficulty, whereas resistance weld units generally cannot be sealed under vacuum. Figure 5.7 shows a typical cold welding set up, incorporating a cryogenic pumping system and automatic control of the welding and vacuum cycle.

5.6 PHOTOLITHOGRAPHIC TECHNIQUES

The techniques described in this and the previous chapter are typical of those used in the processing of conventional resonators of the AT type. Similar techniques are used in the processing of doubly rotated resonators such as the SC-cut, although since these usually will be aimed at very high precision applications, the degree of process sophistication employed will generally be much higher than implied here. Different manufacturing techniques are required, however, for the new generation of miniature resonators such as the miniature GT-cut, tuning fork resonators, and miniature AT bar resonators.

The initial optical processing stages are essentially similar to the corresponding stages of conventional resonators, except that the emphasis is on the

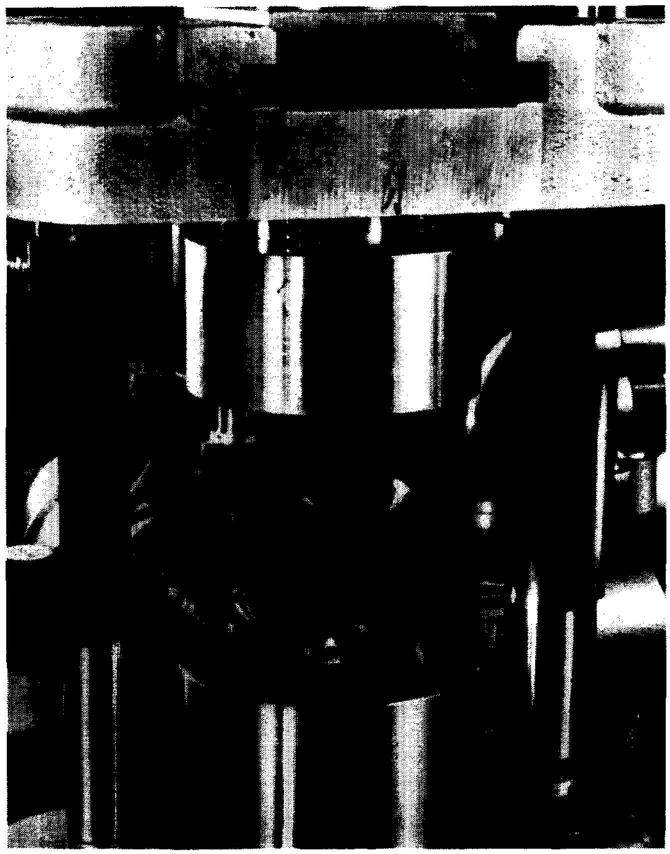

Fig. 5.7 Cold weld press.

production of wafers that may measure one or two inches square, much larger than the conventional crystal blank. From the wafer stage onwards, the processing is much more akin to the production of SAW devices or semiconductor devices than conventional resonators. The key process steps are the use of photolithographic methods, rather than the traditional shadow masks, to define the metallization patterns on the wafer surfaces, and the use of deep etching to separate the individual resonators. More details and further references can be found in the survey by Moore (1983).