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HIGH PRECISION FREQUENCY STANDARD COMPRISING  
SILICON OR GERMANIUM CRYSTAL ELEMENT  
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2,998,575

FIG. 1

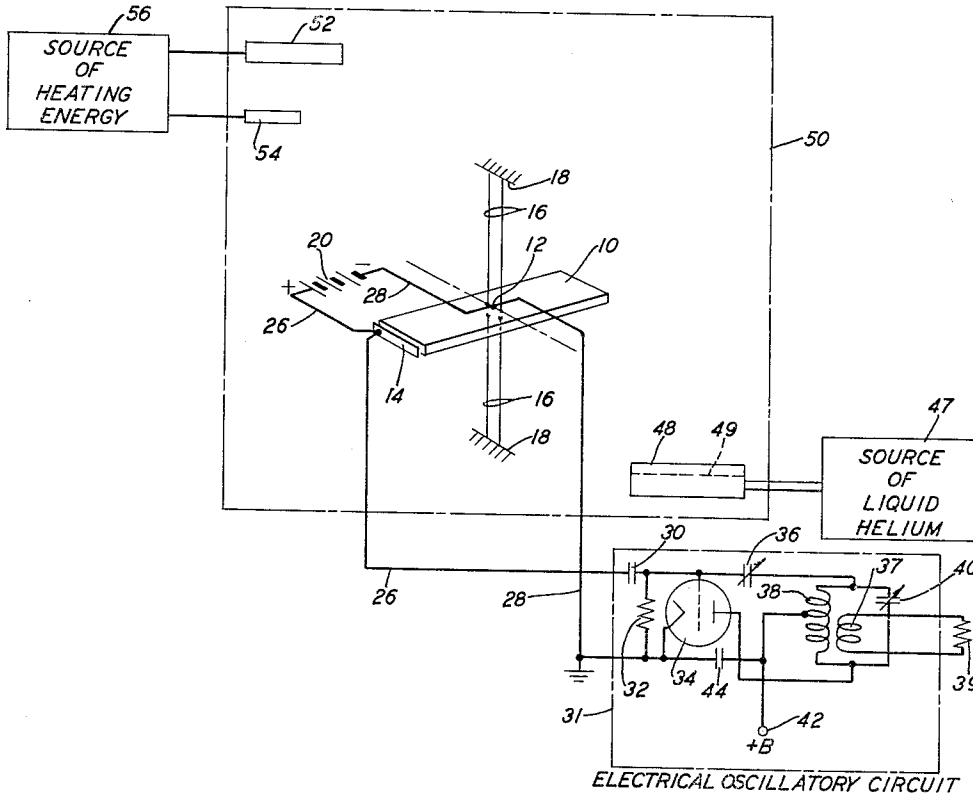


FIG. 2A

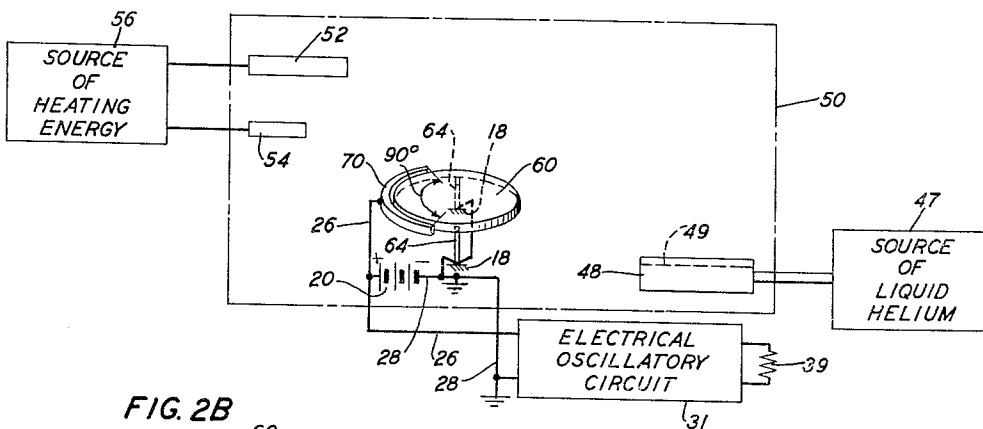
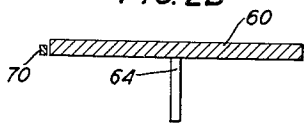


FIG. 2B



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HIGH PRECISION FREQUENCY STANDARD  
COMPRISING SILICON OR GERMANIUM  
CRYSTAL ELEMENTWarren P. Mason, West Orange, N.J., assignor to Bell  
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18 Claims. (Cl. 331-70)

This invention relates to frequency or time standards. More particularly, it relates to such arrangements in which the mechanical vibrations of a physical element are utilized to provide a precise standard of frequency or time.

The most precise standards of frequency or time presently being employed rely upon the piezoelectrically generated vibrations of quartz crystal elements cut at preferred angular orientations with respect to the crystallographic axes of the single crystal from which they are cut.

It is well known, however, that even the best quartz single crystal elements are subject to appreciable aging effects, that is, variations with the age of the crystal, which are believed to be caused by dislocation and relaxation effects within the structure of the element, as discussed for example in the paper of applicant, H. E. Bommel and A. W. Warner, published April 1, 1956, in "The Physical Review," volume 102, No. 1, at pages 64 through 71. Many dislocations in such quartz elements are believed to result from stresses established during the cutting and forming operations required to obtain elements of the specific dimensions and axial alignments required.

The principal object of the present invention is to overcome difficulties resulting from changes with age of high precision frequency or time standards.

In accordance with the invention, this is accomplished by employing as a standard an element cut from a single crystal of silicon or germanium, since such elements have been found to be practically free from aging effects. This is believed to be a result of the fact that no dislocations are generated by the forming stresses.

The application of the principles of the invention will be apparent from the following detailed discussion of the illustrative embodiments shown in the accompanying drawing, in which:

FIG. 1 illustrates one arrangement employing a silicon or germanium element as a frequency or time standard in accordance with the invention; and

FIGS. 2A and 2B illustrate a second such arrangement.

In accordance with further principles of the invention, substantially zero temperature versus frequency characteristics can be obtained with elements of the invention by operating silicon elements at seventy degrees Kelvin or less and germanium elements at thirty degrees Kelvin or less. The pertinent characteristics of silicon and germanium single crystal elements are, for example, discussed in a paper entitled "Measurement of Elastic Constants at Low Temperatures by Means of Ultrasonic Waves—Data for Silicon and Germanium Single Crystals and for Fused Silica," by H. J. McSkimin, published in the Journal of Applied Physics, volume 24, August 1953, pages 988-997. While single crystal silicon and germanium elements cut at any orientation with respect to the crystallographic axes of the single crystal will operate satisfactorily in arrangements of the present invention, it may be somewhat preferable to cut longitudinally vibrating elements with the axis along which they are to vibrate parallel to the [100] crystallographic direction. The conventional Miller crystallographic indices are employed throughout this application. Elements intended

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for transverse vibrational use are preferably cut as thin circular discs and for these it is preferable that the diameter of the disc along which the element is polarized in arrangements of the invention should be parallel to the [100] crystallographic direction.

As an alternative to maintaining the crystal element below the temperatures mentioned above, thermostatically controlled heating means can be supplied to maintain the operating temperature of the element constant. By way of specific example, since silicon has a temperature coefficient of frequency of eighteen parts in a million per degree centigrade, it requires a temperature control to one ten thousandth of a degree centigrade to maintain the frequency within one part in 1,000 megacycles.

As silicon and germanium do not have piezoelectric properties, resort must be had to other means of driving such elements as vibrating elements for use as frequency or time standards. This is readily accomplished, by way of example, by impressing a polarizing field across such an element after which it can be coupled electrostatically to an electrical oscillatory circuit.

In more detail in FIG. 1, an element 10 can comprise, by way of example, a rectangular piece cut from a single crystal of silicon or germanium and having overall dimensions, by way of example, of substantially 3.7 centimeters by one centimeter by two millimeters. Such an element when suspended from its median plane, as, for example, by the fine wires 16, spot welded to the element as indicated in FIG. 1, will have a resonant frequency of longitudinal vibration of substantially 100 kilocycles. By appropriate choice of dimensions for the element 10 a standard for any frequency within the range of fifty to 1,000 kilocycles can be provided.

Since neither silicon nor germanium have piezo-electric properties, it is necessary to provide a polarizing field which, for longitudinal vibration of element 10, can be furnished by connecting a direct current source of voltage 20 across electrodes 12 and 14. Electrode 12 can be merely a spot weld of conductor 28 preferably at the center point of the upper surface of element 10. Electrode 14 is a conductive plate supported adjacent to an end of element 10 with an air gap of three or four thousandths of an inch intervening. Conductive lead 28 connects electrode 12 to the negative terminal of battery 20 and to the grounded input lead to the oscillatory circuit designated generally as 31. Conductive lead 26 connects the positive terminal of battery 20 to electrode 14 and to the ungrounded input lead of oscillatory circuit 31, as shown. For an element of the above described dimensions, i.e., 3.7 centimeters by one centimeter by two millimeters, the voltage applied across electrodes 12 and 14 should be between fifty and 100 volts.

Triode vacuum tube 34 and its associated electrical circuits within the broken line 31 comprise, by way of example, one form of conventional oscillatory circuit suitable for coupling electrostatically to element 10 via extensions of conductive leads 26 and 28 as shown. The specific oscillator illustrated comprises the triode vacuum tube 34 having a cathode, an anode, and a control electrode, as shown, together with the following circuits. The anode circuit comprises the tuning inductor 38 across which is connected the adjustable capacitor 40, a by-pass capacitor 44 connecting the midpoint of inductor 38 to the cathode of tube 34, and an adjustable capacitor 36 connected to the upper terminals of inductor 38 and capacitor 40 to feed back oscillatory energy to the control electrode circuit of tube 34. The anode itself is connected to the lower terminals of inductor 38 and capacitor 40. A source of positive anode potential, not shown, is connected to terminal 42 which in turn is connected to the midpoint of inductor 38. The negative terminal of the

anode potential source, not shown, is grounded. A utilization circuit represented by resistor 39 is coupled to inductor 38 by inductor 37. The control electrode of tube 34 is connected via blocking capacitor 30 and lead 26 to electrode 14, as shown, and via grid leak resistor 32 to the cathode of tube 34. The cathode is connected via lead 28 to electrode 12 and is grounded.

Oscillatory energy from the control electrode and anode circuit of the oscillator (the energy from the latter circuit being fed back through capacitor 36) will tend to excite element 10 into longitudinal vibration, the vibration becoming of maximum amplitude when capacitor 40 is adjusted to tune the anode circuit precisely to the resonant frequency of element 10. In the vicinity of the resonant frequency of longitudinal vibration of element 10, this element will control the oscillation of the circuit with an extremely high degree of precision.

Over the normal range of "room" temperatures and below, elements such as element 10 of FIG. 1 when cut from a single crystal of silicon or germanium will exhibit much smaller aging effects than comparable elements cut from even the best quartz single crystals and hence will not appreciably change their resonant frequencies with age for a specific temperature as will the quartz crystal elements.

At room temperatures and lower, until a temperature of substantially seventy degrees Kelvin (approximately minus 200 degrees centigrade) is approached, an element cut from a single crystal of silicon will, however, exhibit appreciable change of resonant frequency with temperature. Accordingly, element 10 may for this range of temperatures be stabilized by enclosing it in a heat insulating enclosure, indicated by broken line 50, and the temperature within the enclosure can, in accordance with one arrangement, be maintained constant by a heating element 52 within enclosure 50 supplied by an external source of heating energy 56, which source can be conveniently controlled by a thermostat 54, the latter being also within enclosure 50. Numerous and varied suitable temperature controlling arrangements of the general type just described have long been known to and widely used by those skilled in the art, so that a further detailed description is not deemed warranted here. If such an arrangement is used, the reservoir 48, it contents 49, and the source 47, described hereinbelow, are omitted.

An alternative arrangement for avoiding frequency variations with changing temperature is based upon the fact that silicon has been found to have a virtually constant temperature versus resonant frequency coefficient at temperatures of seventy degrees Kelvin and below. Illustrative curves are given in the paper by McSkimin mentioned above. Accordingly, the heating element 52, source 56 and thermostat 54 can be eliminated and a reservoir 48 provided within enclosure 50 in which a sufficient supply of liquid helium 49 is maintained from source 47 to keep the temperature within enclosure 50 at a temperature of seventy degrees Kelvin or less.

The same stability maintenance arrangements can be employed where element 10 is cut from a single crystal of germanium except that germanium must be maintained at a temperature of thirty degrees Kelvin or less if a constant resonant frequency versus temperature is to be realized by cooling the germanium element.

The arrangement of FIG. 2A is in general similar to that of FIG. 1 except that the vibrating element 60 is a disc and is arranged to vibrate transversely rather than longitudinally. This type of vibration is readily adaptable for obtaining stabilizing standards having much higher frequencies of vibration than are feasible with longitudinally vibrating elements such as the element 10 of FIG. 1. For example, with longitudinally vibrating elements, frequencies within the range of fifty to 1,000 kilocycles appear practicable, whereas with disc elements arranged for transverse vibration, frequencies of one to fifteen megacycles appear practicable.

In more detail as shown in the perspective and cross-sectional side views, FIGS. 2A and 2B, disc 60 is cut from a single crystal of silicon or germanium, and for operation at a frequency of two megacycles can be, by way of example, one inch in diameter and 1.47 millimeters thick. Two electrodes comprising respectively the two reeds 64 and the strip 70 are provided. Electrode 70 is spaced adjacent an edge of the disc with an intervening air gap of three or four thousandths of an inch and extends through an arc of ninety degrees. Its vertical dimension parallel to the edge of disc 60 is only half that of the disc as shown more clearly in the enlarged cross-sectional side view of FIG. 2B, the upper edge of the electrode 70 being aligned with the median horizontal plane through the disc 60. Reeds 64 serve also to support disc 60 and can be, for example, metallic reeds each having cross-sectional dimensions of .050 inch by .003 inch. The upper ends of reeds 64 are welded to disc 60 at the opposite ends of the diameter which is parallel to the chord of the arc intercepted by electrode 70. The larger transverse dimension of each reed is parallel to this diameter. The lower ends are firmly held by fixed support 18. Their length is preferably not over 0.25 inch.

A battery 20 is provided to polarize the lower quarter of the lower half of disc 60. Battery 20 may have, by way of example, a voltage of between fifty to 100 volts.

An enclosure 50, a thermostatically controlled temperature regulator system 52, 54 and 56, or alternatively, a supply of liquid helium 47, 48, 49, may be employed as described and for the purposes given in connection with the arrangement of FIG. 1 for the like numbered parts.

Similarly, an electrical oscillatory circuit 31 of the same type as described in connection with the arrangement of FIG. 1 may be used, as described generally for FIG. 1, except that, as will be immediately apparent to those skilled in the art, elements adapted for use at the higher frequency of oscillation should be employed.

The oscillatory circuit 31 of FIG. 2A is connected by its grounded input lead 28 to reeds 64 and by its ungrounded input lead 26 to electrode 70, as shown.

Numerous and varied other arrangements and circuit connections within the spirit and scope of the principles of the invention will readily occur to those skilled in the art. No attempt to illustrate all such arrangements has here been made.

What is claimed is:

1. A frequency standard comprising a member cut from a single crystal of the class consisting of silicon and germanium, the dimensions of the member being proportioned for mechanical resonance of the member in a specific mode of vibration at a specific frequency, means for supporting the member for the specific mode of vibration, means for establishing the specific mode and the specific frequency of mechanical vibration of said element, and means for utilizing said vibration.
2. The standard of claim 1, the member being cut from a single crystal of silicon.
3. The standard of claim 2, and means for maintaining the temperature of the member constant.
4. The standard of claim 2, and means for maintaining the temperature of the member at seventy degrees Kelvin, or less.
5. The standard of claim 1, the member being cut from a single crystal of germanium.
6. The standard of claim 5, and means for maintaining the temperature of the member constant.
7. The standard of claim 5, and means for maintaining the temperature of the member at thirty degrees Kelvin, or less.
8. A standard of frequency and time comprising an element cut from a single crystal of the class consisting of silicon and germanium, the dimensions of the element being proportioned for mechanical resonance of the element in a specific mode of vibration at a specific frequency, means for supporting the element for the specific mode

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of mechanical vibration, means for polarizing the element, and an electrical oscillatory circuit having a nominal frequency of oscillation substantially equal to the specific frequency of resonance of the element and electrostatic coupling means coupling the element to the circuit to control oscillation of the circuit.

9. The standard of claim 8, the element being cut from a single crystal of silicon.

10. The standard of claim 8, the element being cut from a single crystal of germanium.

11. The standard of claim 8 in which the element is rectangular.

12. The standard of claim 11 in which the coupling means is coupled to a longitudinal mode of vibration of the element.

13. The standard of claim 8 and means for maintaining the temperature of the element constant.

14. The standard of claim 8 and means for maintaining the temperature of the element at thirty degrees Kelvin or less.

15. The standard of claim 8 in which the element is of rectangular shape and the supporting means support the element for longitudinal vibration.

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16. The standard of claim 8 in which the element is a disc, the polarizing means polarize an unsymmetrically positioned portion of the element, and the supporting means support the element for transverse vibration.

17. The standard of claim 16 and means for maintaining the element at constant temperature.

18. The standard of claim 16 and means for maintaining the element at a temperature of thirty degrees Kelvin or less.

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