Miniaturization of Tuning Forks

Integrated electronic circuits provide the incentive and the means for orders-of-magnitude reduction in size.

William E. Newell

Tuning forks and other forms of flexural mechanical resonators are widely used in stable, fixed-frequency filters and oscillators for frequencies of 50 kilohertz or less. During the past 25 years, conventional tuning forks have been reduced in weight and volume by a factor of 100 (*1*). The recent development of integrated electronics has made a reduction in their size by many more orders of magnitude desirable. Indeed, devices have been demonstrated, and are being developed (*2*), in which the mechanical resonator has a volume some one million times smaller than that of conventional miniaturized tuning forks.

Therefore the question arises, How small can such resonators ultimately be made? It is a truism that fabrication technology tends to evolve so as to make economically practical the manufacture of any device which it is physically possible to make, if it is sufficiently useful. My purpose in this article is to consider the fundamental problems associated with flexural resonators and to see how these problems are affected by scaling down the size—that is, to see what "trade-offs" in performance are imposed by fundamental physical limitations (as distinguished from problems of fabrication with current technology) when the size of these resonators is reduced by several orders of magnitude. It is concluded that, in many applications where Q factors of the order of 100 are needed, flexural resonators which are compatible in size with integrated circuits are physically adequate, although fundamental problems are encountered in trying to operate at signal levels of less than tens of millivolts or at frequencies outside the range from 1 kilohertz to 1 megahertz. Because of the fundamental problems also encountered with alternative means of incorporating frequency selectivity into monolithic integrated circuits (*3*), the development of integrated flexural resonators that will operate within these characteristic signal-level and frequency boundaries continues to be a very promising approach. In this article the characteristics of two flexurally resonant devices which are compatible in size and fabrication requirements with integrated circuits are described briefly.

The author is affiliated with the Westinghouse Research Laboratories, Pittsburgh, Pennsylvania. This article is adapted from a paper presented 5 September 1967 at the Conference on Solid State Devices, Manchester, England.

Generalized Electromechanical Tuned Device

The stimulus for the investigation discussed has been the continuing lack of a suitable means of incorporating frequency selectivity into a completely monolithic silicon integrated circuit. We are very close to nearly universal application of such integrated circuits, in conjunction with film integrated circuits where necessary, in all electronic information-processing systems. With the exception of the individual digital computer, in which the greater part of the information flow is internal, most of these systems require information transfer over appreciable distances. Efficient transmission of information over such distances usually requires modulation of a carrier frequency. Therefore a large proportion of the systems in which integrated circuits will ultimately be used will require frequency selectivity. A significant advantage in reliability and size—and, hopefully, also in cost—would be achieved if this function could be performed within the integrated circuit and if the circuit could be built by technology compatible with batch fabrication.

It would seem, from considerations of size alone, that mechanical resonators offer a promising solution to this problem of providing integrated tuned devices over a wide frequency range (*4*). With such a tuned device, electromechanical transducers would also be needed to convert the input electrical signal into a force and the resulting vibration into an output electrical signal (*5*). Figure 1 shows schematically a generalized electromechanical tuned device, various modes of resonance, and various transducer mechanisms that can be used. For reasons discussed below I confine my attention to flexural resonators. Later in the article I consider electrostatic and piezoelectric transducers that seem to be appropriate for very small tuned devices.

Effect of Aspect Ratio

The thickness of a thickness-mode resonator is determined by the desired frequency of operation and by the velocity of sound in the material. The lateral dimensions are determined by considerations of impedance and energy trapping. Therefore there is very little possibility of miniaturizing this type of resonator, at least of miniaturizing it by several orders of magnitude.

On the other hand, the resonant frequency f_r of a flexural resonator depends on an aspect ratio, and this makes it possible to change the size of the resonator while holding resonant frequency constant. For example, the resonant frequency of a uniform cantilever (*6*) of length L and thickness d is given by

$$\omega_r = 2\pi f_r = 1.03(d/L)(1/L)(Y/\rho)^{1/2} \quad (1)$$

where ω_r is the radian frequency of the resonance, Y is Young's modulus, and ρ is the mass density. Figure 2 shows the effect of the length-to-thickness ratio, L/d, for a material having an acoustic velocity $(Y/\rho)^{1/2}$ of 2000 meters per second. A cantilever having a resonant frequency of 3 kilohertz and L/d of 10 must be about 1 centimeter long, but if L/d can be increased to 1000, the length drops to 0.1 millimeter. Moreover, the volume of the resonator decreases as the fourth or fifth power of L/d, depending on whether the width is varied in proportion to the length or the thickness. Therefore the question "How small can a flexural resonator be made?" is equivalent to the question "How large can L/d be made?"

The approach in this article is to consider the rate of change of the important characteristics with change in L/d for a cantilever, which is probably the simplest of all flexural resonators. For this purpose, qualitative estimates based on the simplest possible models are of greater interest than quantitative precision. Use of more elaborate models may improve the precision but will not significantly change the conclusions based on the qualitative estimates.

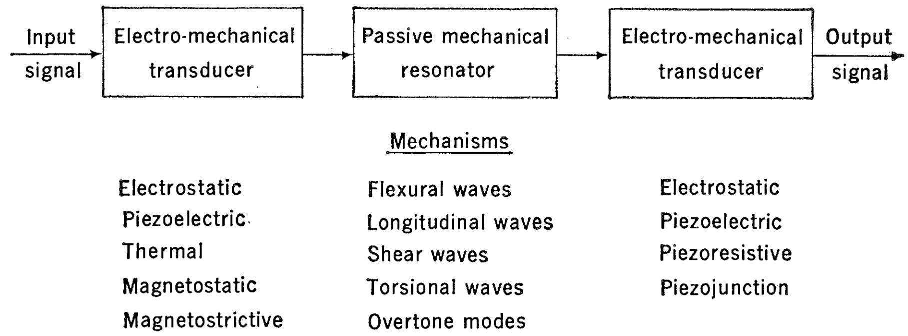


Fig. 1. Schematic diagram of a generalized electromechanical tuned device, with some suggested physical transducer mechanisms and modes of vibration.

Gravitational Effects

A mechanical resonator is affected by inertial forces caused by externally imposed accelerations (including gravity) as well as by forces from the input transducer. Ordinarily it is undesirable to operate with an amplitude of vibration at resonance which is smaller than the gravitational deflection due to the resonator's own weight. The end deflection of a horizontal cantilever due to the cantilever's own weight (that is, δ_g) is given by the equation

$$\delta_g = \frac{3}{2} \cdot \frac{WL^3}{Ywd^3} = \frac{3}{2} \cdot \frac{\rho w d L^4}{Ywd^3} g = \frac{3}{2} \cdot \frac{(0.1615)^2}{f_r^2} g = \frac{0.38}{f_r^2} \text{ meters} \quad (2)$$

where W is the weight of the cantilever, w is its width, and g (= 9.8 m sec^{-1} sec^{-1}) is the gravitational acceleration. Constant external acceleration causes a uniform deflection per g of acceleration, while sinusoidal acceleration at the resonant frequency causes a deflection which increases by a factor of about Q per g. This deflection is a serious problem in all low-frequency mechanical resonators because it increases inversely as the square of the resonant frequency. However, as may be seen from Eq. 2, it is independent of L/d and therefore does not increase for small resonators.

Gravity also affects the frequency of a mechanical resonator if the particle vibration does not follow a straight line. That is, there is a component of the gravitational force which opposes the mechanical restoring force and decreases the resonant frequency when a cantilever is clamped at its lower end but increases the resonant frequency when the clamp is at the upper end. It can be shown that the frequency difference, Δf, of these positions relative to the horizontal position is given approximately by the equation (see 7)

$$\frac{\Delta f}{f_r} \approx \pm \frac{1}{6Lf_r^2} \quad (3)$$

when L is expressed in meters and f_r, in hertz. A more meaningful form of Eq. 3 is obtained when the frequency shift due to gravity is expressed as a proportion of the bandwidth, f_r/Q:

$$\frac{\text{Frequency shift}}{\text{Bandwidth}} = Q \frac{\Delta f}{f_r} \approx \pm \frac{Q}{6Lf_r^2} \quad (4)$$

For a tuning fork 1 centimeter long resonating at a frequency of 1 kilohertz, this shift is only $\pm$ 1/60 hertz or $\pm$ 1.7 percent of the bandwidth for Q = 1000. The effect rapidly becomes more significant for lower resonant frequencies. Also, if the length of the tuning fork is reduced to 1 millimeter while the resonant frequency and Q are held constant, the shift increases to 17 percent of the bandwidth. However, the reduction in size also usually causes a reduction in Q, as discussed below, so that the shift may not be larger relative to the bandwidth.

Suffice it to say that gravity and other external accelerations lead to problems in all mechanical devices having a low resonant frequency, particularly when the resonant frequency is 1 kilohertz or less. These problems, while deserving serious attention, are not necessarily a limiting factor which will prevent much greater miniaturization of tuning forks than has been achieved.

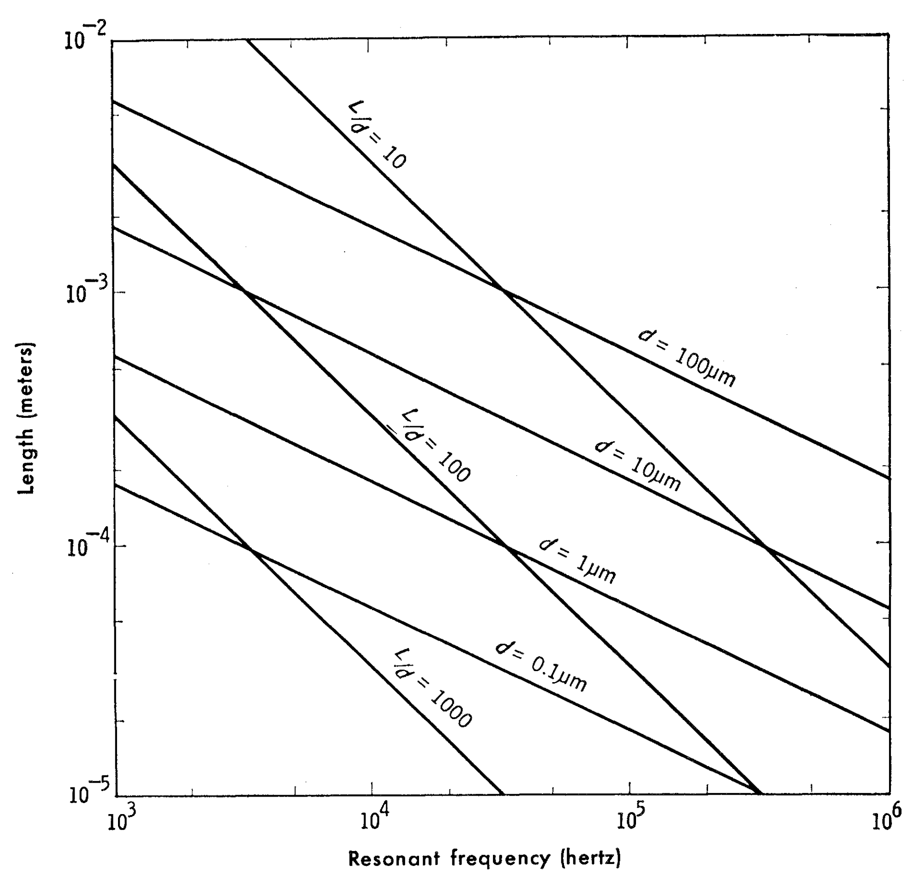


Fig. 2. The effect of length-to-thickness ratio (L/d) on the size of a cantilever resonator. The resonant frequency (f_r) of a cantilever = 0.1615 (d/L) ($1/L$) $(Y/\rho)^{1/2}$.

Vibration Due to Thermal Agitation

In a conventional tuning fork, thermal agitation of the molecules leads to a vibration which is insignificant, but as the tuning fork is miniaturized the thermal vibration becomes progressively more significant. For a system with one degree of freedom, the mean potential energy due to thermal agitation is ½ kT (k is Boltzmann's constant and T is absolute temperature). This noise energy may be equated to the potential energy stored in the resonator with effective spring constant K and root-mean-square deflection δ_N. Therefore,

$$\frac{1}{2} K\delta_N{}^2 = \frac{1}{2} kT;$$

from this we obtain

$$\delta_N = (kT/K)^{1/2} = (kT/M)^{1/2} \ (M/K)^{1/2} = (kT/M)^{1/2} \ (1/\omega_r) \quad (5)$$

where M is the effective mass of the resonator and ω_r is $(K/M)^{1/2}$. Equation 5 shows that, at constant frequency, as the resonator is miniaturized and the mass is reduced, the amplitude of thermal vibration increases.

One may relate the thermal vibration of a cantilever to the aspect ratio L/d by substituting an effective spring constant in Eq. 5; this gives

$$\delta_N = (kT/K)^{1/2} = (2kT/wY)^{1/2} \ (L^3/d^3)^{1/2} \quad (6)$$

The factor $(2kT/wY)^{1/2}$ may be considered a characteristic thermal deflection which is dependent only on the width of the resonator and on Young's modulus (and on absolute temperature). An increase in this characteristic deflection by $(L/d)^{3/2}$ gives the actual deflection. Except in the case of extremely small resonators and high frequencies, the amplitude of the thermal vibration is much smaller than δ_g, the deflection due to gravity, and therefore does not impose an additional constraint on the possible miniaturization.

Limiting Effect of Fatigue

The effects of acceleration and thermal agitation set a lower limit on the amplitude of signal vibrations which are practical in a mechanical resonator. The dynamic range of such a device is also limited at the upper end by fatigue, and it is of interest to determine whether fatigue becomes increasingly important with miniaturization.

For a force, F, applied to the end of a uniform cantilever, the end deflection δ and the maximum stress $\tau_{\max}$ (which occurs at the clamped end) are

$$\delta = \frac{4FL^3}{Ywd^3} \quad (7)$$

and

$$\tau_{\max} = \frac{6FL}{wd^2} \quad (8)$$

Solving Eq. 8 for F and substituting in Eq. 7 gives

$$\delta = \frac{2}{3} \cdot \frac{L^2\tau_{\max}}{dY} = \frac{2}{3} \cdot \frac{\tau_{\max}}{\omega_r(Y\rho)^{1/2}} \quad (9)$$

Equation 9 relates the maximum stress to the deflection at a specified resonant frequency. If the maximum stress permitted by fatigue is assumed to be independent of frequency, then the maximum deflection permitted by fatigue is inversely proportional to frequency. However, this maximum deflection is independent of L/d. Therefore we conclude that fatigue does not prevent miniaturization.

Air Damping

Of the effects so far considered, only thermal vibration and the frequency shift due to attitude have been found to increase as a cantilever resonator is miniaturized. On the other hand, air damping increases rapidly as the resonator's volume-to-surface ratio decreases. This damping, although it can be avoided by vacuum encapsulation of the resonator, is probably the most significant factor in determining what degree of miniaturization is feasible. To analyze how the damping (or Q) of a cantilever varies with air pressure and with L/d, we divide the pressure range from vacuum to atmospheric pressure into three regions.

In the first region the pressure is so low that air damping is negligible as compared to damping within the resonator. This internal or "intrinsic" damping is determined by the resonator material and the method of fabrication as well as by the volume-to-surface ratio (since the surface tends to be considerably more lossy than the bulk material). However, there seems to be no simple theoretical model which permits prediction of this intrinsic damping and the corresponding Q. Thus, at very low pressures the intrinsic Q is independent of pressure and must be determined empirically.

In the second pressure region, air damping becomes the dominant mechanism, but the air molecules are so far apart that they do not interact with each other. The damping may be analyzed in terms of a simple model in which individual air molecules exchange momentum with the resonator at a rate proportional to the difference in velocity between the air molecules and the resonator. This damping is proportional to air pressure (*8*) and yields a Q given by the equation

$$Q = (\pi/2)^{3/2}\rho d f_r[(R_0T/M_0)^{1/2}/(1/P)] \approx 93(d/L)^2[(Y\rho)^{1/2}/P] \quad (10)$$

when $T = 300°\text{K}$ and Y and ρ (like R_0, M_0, and P) are in meter-kilogram-second units. Here $R_0 = 8317$ joules per degree Kelvin (= the universal gas constant); M_0 = molecular mass (= 29 kilograms for air); and P = air pressure, in newtons per square meter. (Substitution of the value for f_r obtained from Eq. 1 gives the second form of Eq. 10.) It may be seen that Q, in this pressure region, is inversely proportional to the square of L/d, and is therefore strongly influenced by miniaturization.

For the third pressure region, the assumption that the air molecules do not interact breaks down. A more reasonable assumption is that the air acts as a viscous fluid. Since viscosity is independent of pressure, in this region Q is also independent of pressure. Using Stokes' law for the damping force per unit area, we obtain

$$Q = [(Y\rho)^{1/2}w/24\mu](d/L)^2 \quad (11)$$

where μ = viscosity (= 1.8×10^{-5} newton sec m^{-2} for air). Note that, in this pressure region, Q is also inversely proportional to $(L/d)^2$. To obtain an estimate of the pressure P where the damping changes from that typical of region 2 to that typical of region 3, we may equate Eqs. 10 and 11; this gives

$$P = \frac{4 \times 10^{-2}}{w(\text{m})} \text{ newton sec m}^{-2} = \frac{0.3}{w(\text{mm})} \text{ torr} \quad (12)$$

Thus, for all conventional resonator widths (that is, widths greater than 0.4 micrometer) the pressure given by Eq. 12 is less than 1 atmosphere, and Q, when the resonator is operated in air, is that characteristic of pressure region 3.

In using Stokes' law for deriving Eq. 11 we assume that the resonator is isolated. If the resonator is close to another stationary surface, the region-3 damping is further increased because of the pumping action on the air in the intervening space. By using another simple model based on the drop in pressure in a viscous fluid flowing through a parallel-walled duct, we find the Q equation for a resonator at a distance Δ_0 from a stationary surface to be

$$Q = [(Y\rho)^{1/2}w/\mu](d/L)^2(\Delta_0/w)^3 \qquad (13)$$

Comparison of Eqs. 11 and 13 shows that Eq. 13 contains an additional factor of $24(\Delta_0/w)^3$. Therefore Eq. 13 holds when the space between the resonator and the stationary surface is less than about one-third the width of the resonator, and Q is then very sensitive to this spacing.

Figure 3 shows plots of Eqs. 10, 11, and 13 for values which are typical for the resonant gate transistor described in the next section. These graphs are quantitatively consistent with experimental measurements of Q. It may be seen that both high values of L/d and close proximity of the resonator to a stationary surface cause significant reductions in Q at atmospheric pressure. This seems to be the dominant limitation that determines the ultimate feasible miniaturization of flexural resonators.

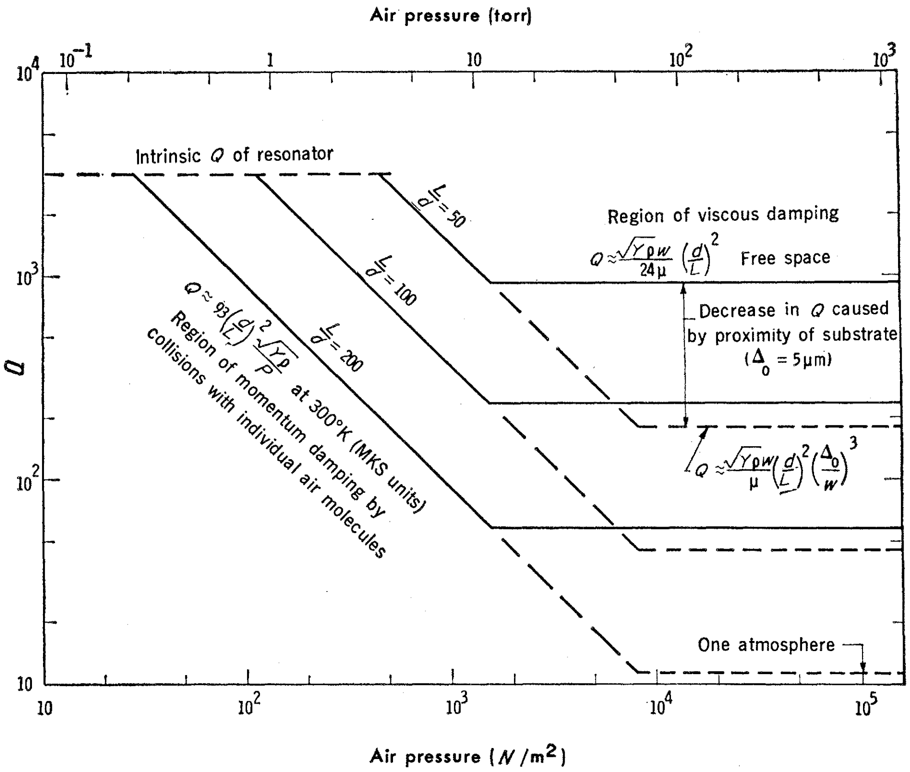


Fig. 3. Variation of Q with air pressure for resonators having various length-to-thickness ratios. Assumed values: $(Y\rho)^{1/2} = 4 \times 10^7$ kg m^{-2} sec^{-1}; $\mu = 1.8 \times 10^{-5}$ newton sec m^{-2}; $w = 25$ μm.

Resonant Gate Transistor

The resonant gate transistor (RGT) (*2*) is the device referred to above as having a miniature cantilever resonator some million times smaller in volume than conventional miniaturized tuning forks. Hundreds of these devices can be fabricated simultaneously on a silicon wafer 1 inch (2.54 centimeters) in diameter, by means of planar integrated circuit technology. Although the RGT exemplifies the tolerance problems encountered in manufacturing all precision tuned devices, it also illustrates the validity of the prediction, based on the foregoing analysis, that reductions in size by several orders of magnitude are possible. Results achieved with this device are compared below to results of the analysis of the simple models.

The geometry and circuit connections of the RGT are shown schematically in Fig. 4. In the input transducer, electrostatic attraction is used to excite vibrations of the cantilever resonator. Because electrostatic force varies as the square of the voltage, a constant polarization voltage, V_p, is required. Vibration of the cantilever causes a variation in the polarization field, which is sensed by a surface field-effect transistor, of which the cantilever is the "gate" or control electrode (hence the name resonant gate transistor). Figure 5 shows a 1-inch silicon wafer containing some 500 RGT's, together with a magnified view of an individual device. The cantilever resonators are of gold, which is electroplated onto a temporary metal spacer layer that is later etched away. The choice of gold has been dictated by the availability, to date, of low-stress electroplating solutions for gold only.

Analysis of the circuit including the electrostatic input transducer gives an expression of the following form for the deflection, δ_r, of the cantilever at its resonant frequency:

$$\delta_r \approx \eta\, Q(V_p/V_{pi})[(L/d)^3(L/\Delta_0)(\epsilon_0/Y)V_{in}]^{1/2} \qquad (14)$$

where η = a dimensionless constant factor which depends on the length and position of the input force plate and is typically about 0.2; V_{pi} = "pull-in" voltage—that is, the limiting value of V_p at which the cantilever is pulled into contact with the substrate; ϵ_0 per-

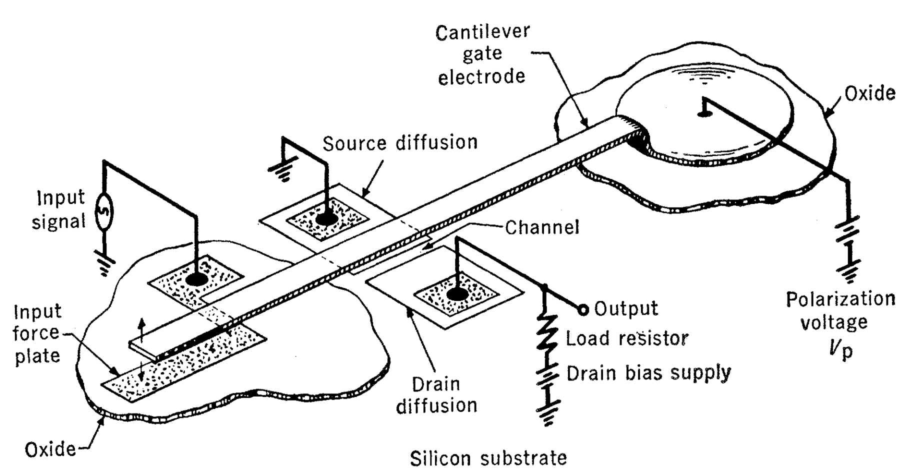
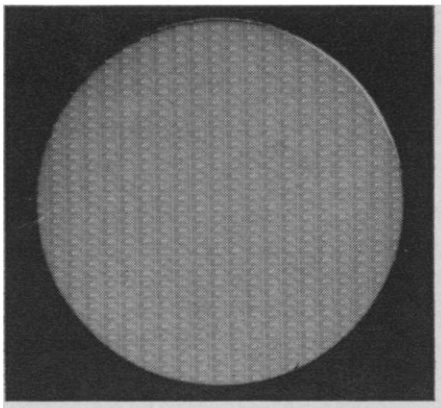


Fig. 4. Schematic diagram of the geometry and circuit connections of the resonant gate transistor.



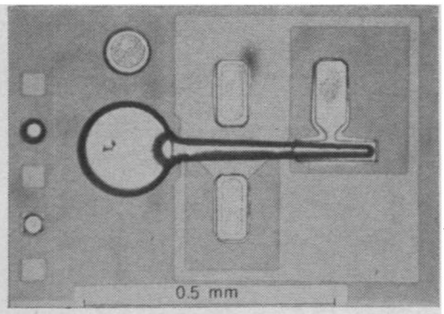


Fig. 5. (Left) One-inch (2.54-centimeter) silicon wafer containing some 500 resonant gate transistors. (Above) Magnified view of a resonant gate transistor.

mittivity (that is, dielectric constant) of air (= 8.85×10^{-12} f/m); and V_{in} = input signal voltage.

The RGT is normally operated with $V_p/V_{pi} \approx 0.5$. If we use $Y = 8 \times 10^{10}$ newton/m^2 for gold, and use the other values listed above, we may write Eq. 14 as follows:

$$\delta_r \approx 10^{-6}Q(L/d)^{3/2}(L/\Delta_0)^{1/2}V_{in} \text{ micrometers} \quad (15)$$

For typical dimensions such as $L = 0.5$ millimeter, $d = \Delta_0 = 5$ micrometers (for which Eq. 1 predicts a resonant frequency of about 6.5 kilohertz), and $Q = 100$, Eq. 15 gives a deflection of 1 micrometer for an input signal of 1 volt. With Q set equal to 100, Eq. 13 can be solved for the width, giving 17 micrometers, a value which is also typical (9).

A design chart may be formulated for comparing the calculated value for deflection due to a signal to the calculated values for deflections due to gravitation or thermal agitation or for the deflection permitted by fatigue. Since the gravitational deflection sets the practical lower limit over most of the frequency range, the other deflections are normalized with respect to it.

The resulting design chart is shown in Fig. 6. Graphs of Eq. 15 are plotted for constant values of L/d equal to 50, 100, and 200, and arbitrarily assigned values of $Q = 100$, $V_{in} = 1$ volt, $L/\Delta_0 = 100$, and $V_p/V_{pi} = 0.5$. Superimposed on these graphs are the limiting lines of constant resonator length and thickness. These limits are not fundamental but are reasonable estimates of what is feasible with present fabrication technology. Note that these limits form a box within which the designer may choose from a range of L/d values for a specified resonant frequency. This box shifts vertically upward or downward if the input signal is greater than or less than the assumed 1 volt. Note that the range of frequencies over which the RGT can be built to operate at present extends from about 1 to 50 kilohertz. At the low end of this frequency range it is impossible to get a Q of 100 without decreasing the air pressure or decreasing L/Δ. At the high end of the frequency range it may be impractical to make the resonator width large enough to reduce Q to 100. In other words, the design chart must be interpreted with some caution, but it does indicate in a general way what is important. For example, it shows that fatigue is unimportant until the signal level is raised to about 10 volts (10). However, the signal deflection becomes an appreciable fraction of the spacing, Δ_0, and nonlinearity sets in at a typical signal level of several volts. At the opposite extreme, it may be seen that the device cannot be used at signal levels in the microvolt range because the signal deflection is then much smaller than the gravitational deflection (11). Figure 6 also shows that thermal agitation is not a determining factor in the frequency range attainable by the resonant gate transistor as now fabricated.

With respect to miniaturization, Fig. 6 shows that, at a specified resonant frequency, L/d should be made as large as fabrication technology permits, to achieve operation at reduced signal levels. The limitation on the foregoing statement is that either L/d must be small enough to make the desired Q a possibility or else the device must be operated at reduced air pressure. An increase in L/d has the additional advantage that the device thereby occupies a smaller area of the silicon wafer, thus more devices can be placed on each wafer.

Several main problem areas in connection with the RGT are listed below.

1) Fabrication techniques do not yet provide adequate control of resonant frequency and Q. This problem is encountered with any new tuned device, but it is especially severe in this case since the RGT represents a radical departure from earlier devices.

2) No technique compatible with the planar technology used in fabricating integrated circuits has yet been found for using a low-temperature-coefficient resonator material (for example, the various nickel-iron alloys having zero temperature coefficients). The temperature coefficient of frequency for gold is

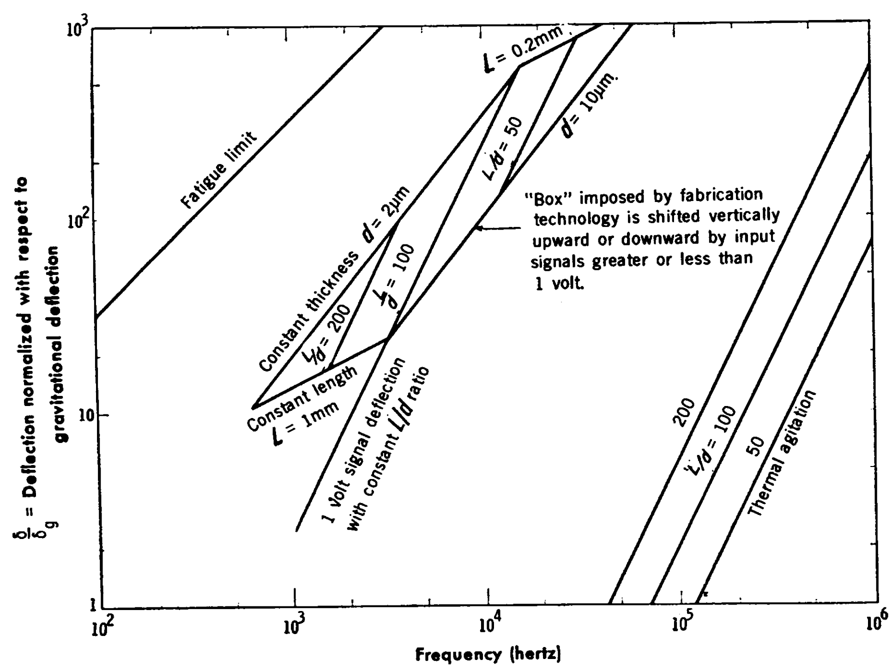


Fig. 6. Design chart for a resonant gate transistor. Assumed values, for gold: $Y = 8 \times 10^{10}$ newton/m^2; $\rho = 2 \times 10^4$ kg/m^3; $\tau_{max} = 4 \times 10^7$ newton/m^2.

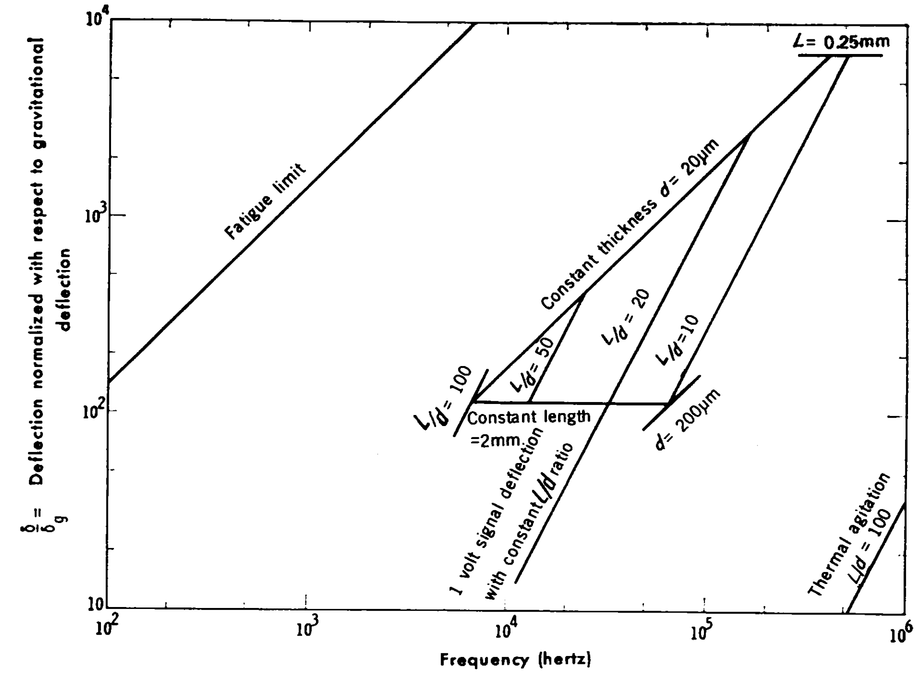


Fig. 7. Design chart for a silicon cantilever tunistor. Assumed values: $V_{in} = 1$ volt, $Q = 100$; for cadmium sulfide, $(d_{31}/s_{11}) = 0.25$ coulomb/m²; for silicon, $Y = 1.7 \times 10^{11}$ newton/m², $\rho = 2.3 \times 10^3$ kg/m³, $\tau_{max} = 10^8$ newton/m².

about 120 parts per million per degree centigrade, and in practice this value is several times higher when the polarization voltage is high enough to give a reasonable insertion loss. However, this problem may be minimized in various ways by means of compensation or through thermal stabilization of the silicon chip.

3) As mentioned above, the highest frequency at present attainable with the RGT is about 50 kilohertz. Higher frequencies have been achieved by using a resonator clamped at both ends (a "clamped-clamped" resonator geometry) in place of the cantilever, but differential expansion between the gold resonator and the silicon substrate led to excessively high temperature coefficients of frequency. Many potential applications for integrated circuits require filters and stable oscillators at considerably higher frequencies.

4) A polarization voltage of 20 to 70 volts is normally needed by the RGT, and a voltage this high is not readily available in most transistor circuits.

To summarize, the RGT has demonstrated that it is physically possible to reduce the size of flexural resonators by several orders of magnitude without destroying their desirable properties (as happens, for instance, when an inductor is miniaturized). Some of the problems encountered in the miniaturization process may be solved or lessened through intensive development work on fabrication technology. Other problems may be more easily solved by seeking to develop new devices which, while retaining basic compatibility with integrated circuits and conforming to the generalized scheme of Fig. 1, have more appropriate transducer mechanisms or modes of vibration, or both. Work is now in progress on a device, called the tunistor, which suggests some of the possibilities of the latter approach.

The tunistor (*12*) was devised in an attempt to lessen some of the problems encountered with the resonant gate transistor. It differs from the RGT in two important ways: (i) silicon is used as the resonator material; (ii) recently developed piezoelectric film transducers (*13*) are used in place of electrostatic transducers. The first change avoids the problems associated with depositing the resonator material but replaces them with problems of forming the resonator from the substrate silicon (for example, by etching). However, the advantages include a temperature coefficient of frequency of only about 40 parts per million per degree centigrade (*14*) and the possibility of using a clamped-clamped or a free-free resonator geometry for achieving higher frequency without the associated problem of differential expansion. The second change eliminates the need for a polarization voltage and avoids the associated effects on gain and frequency, the need to control Δ_0 (the spacing between cantilever and substrate), and the noise resulting from the exposed field-effect transistor. Replacing these problems are those of depositing and defining a high-quality piezoelectric film such as cadmium sulfide.

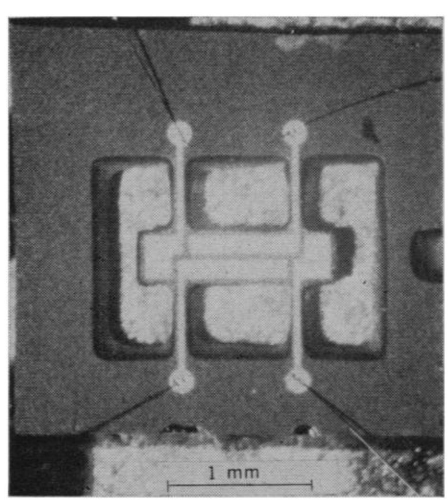


Fig. 8. Tunistor etched from silicon. Resonator length, 1.25 millimeters. Piezoelectric film transducers of cadmium sulfide.

It can be shown that δ_r, the deflection of a cantilever tunistor at its resonant frequency, is given approximately by the equation

$$\delta_r = (3Q\eta d_{31}/Ys_{11}[(L/d)^2]V_{in} \quad (16)$$

where η = a dimensionless constant, estimated to be about 0.2, that depends on the area and position of the input transducer electrode; d_{31} = the piezoelectric coefficient of the film transducer ($= 5.2 \times 10^{-12}$ coulomb/newton for cadmium sulfide); s_{11} = compliance of the piezoelectric film ($= 2.1 \times 10^{-11}$ m²/newton for cadmium sulfide); Y = Young's modulus of the silicon resonator ($= 1.7 \times 10^{11}$ newton/m²; and L and d = the length and thickness, respectively, of the silicon resonator.

Figure 7 is a design chart for the silicon cantilever tunistor. The range of dimensions which is assumed to be feasible includes lengths from 0.25 millimeter to 2 millimeters and thicknesses from 20 to 200 micrometers. The design chart for a free-free resonator would be similar, except that the resonant frequency would be increased by a factor of about 2π.

Silicon tunistors with free-free flexural resonators supported at their nodes have been demonstrated. A typical device having a resonator length of 1.25 millimeter is shown in Fig. 8. Gold electrodes are so arranged that the input voltage is applied across a cadmium sulfide film deposited on the silicon surface, and arranged to yield an output voltage when the resonator bends. The resonant frequency of these tunistors is near 250 kilohertz, and Q's of 500 or more are obtained with operation in air. The expectation that the temperature coefficient of frequency would be about 40 parts per million per degree centigrade has been confirmed. Similar devices with frequencies to several megahertz should be feasible, and active elements can be added to yield a monolithic tuned integrated circuit with net gain.

Conclusions

Flexural resonators similar to tuning forks offer an attractive way of obtaining stable, high-Q frequency selectivity in monolithic integrated electronic circuits. Size compatibility with these circuits requires orders-of-magnitude reduction in the dimensions of present tuning forks. The consequences of this degree of miniaturization are investigated here. It is concluded that vibration-sensitivity and fatigue remain dominant limiting factors, but that they are *not* made more severe by miniaturization. Frequency shift due to gravitational effects and vibration caused by thermal agitation are increased by miniaturization, but it is shown that these are still not ordinarily the dominant limitations. Air damping rapidly decreases the Q of a resonator when it is miniaturized, but Q's of the order of 100 remain feasible for resonators small enough to be incorporated in integrated circuits. Higher Q's can be obtained by means of encapsulation of the device in a vacuum.

Two devices are described which have demonstrated that flexural resonators can be fabricated by techniques which are compatible with the planar integrated circuit process. The resonant gate transistor has useful applications in the frequency range from 1 to 50 kilohertz; the tunistor extends this range to several megahertz.

The results presented here indicate that the smallest flexural resonators fabricated today do not represent the ultimate miniaturization which is physically possible. Therefore it is predicted that there will be further reduction in the size of such resonators. The challenge which continues to face us is the problem of developing the radically new techniques needed for economically fabricating microscopic resonators with adequate tolerance control. Integrated circuits provide both the incentive and the means for solving this problem.

References and Notes

1. F. Dostal, in *Proceedings 19th Annual Symposium on Frequency Control* (U.S. Army Electronics Command, Fort Monmouth, N.J., 1965), pp. 59–77.
2. H. C. Nathanson, W. E. Newell, R. A. Wickstrom, J. R. Davis, *IEEE (Inst. Elec. Electron. Eng.) Trans. Electron Devices* **14**, 117 (1967).
3. W. E. Newell, *Proc. IEEE (Inst. Elec. Electron. Eng.)* **52**, 1603 (1964).
4. ———, *ibid.* **53**, 1305 (1965).
5. A two-terminal device in which a single bilateral transducer serves both functions is preferable in some applications. The same basic considerations apply.
6. A tuning fork differs from a cantilever only in that, in the tuning fork, the reaction force is canceled by a second cantilever vibrating antisymmetrically.
7. M. Hetzel, *Bull. Ann. Soc. Suisse Chronomet. Lab. Suisse Rech. Horl.* **4**, 666 (1962); J. J. O'Connor, *Proc. IRE (Inst. Radio Eng.)* **48**, 1857 (1960).
8. R. G. Christian, *Vacuum* **16**, 175 (1966).
9. When operated in a vacuum, an RGT exhibits a Q of several thousand, so quite high Q's are a possibility if encapsulation at reduced pressure is feasible.
10. Demonstrating the predicted lack of fatigue effects even in a gold resonator, an RGT has been in continuous operation for some 18 months ($\sim 10^{12}$ vibrations) with no significant frequency shift.
11. Another factor that prevents use of the RGT at these signal levels is the broadband noise arising in the channel of the field-effect transistor. This noise is typically equivalent to about 10 millivolts of input signal for present RGT's.
12. W. E. Newell, R. A. Wickstrom, D. J. Page, "Tunistors—mechanical resonators for microcircuits," paper presented at the I.E.E.E. International Meeting on Electron Devices, Washington, D.C., October 1967.
13. J. deKlerk and E. F. Kelly, *Rev. Sci. Instrum.* **36**, 506 (1965).
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NEWS AND COMMENT

Czech Science: Settling Down to Living with the Occupation

Prague. At about noon on the day following the occupation of Prague, a Soviet Army officer led an armed contingent into the big, gloomy former bank building that serves as the administrative center of the Czechoslovak Academy of Sciences. He presented an order that read: "I, Lieutenant Orlov Yuri Alexandrovich, in the name of the Warsaw Pact Armies, order that work be stopped as of 1 p.m. August 22. All workers and members are to leave the building until further notice." As did their countrymen throughout the nation, staff members tried to argue the troops into leaving. "They told us," an Academy employee recalled, "that they had come to protect us from hooligans and counter-revolutionaries." Academy President František Šorm, an internationally renowned chemist, issued a statement that declared, "There is no precedent for such an order in the history of our science. . . . I protest against this unlawful act."

Precedents and legalities were, of course, no concern of the occupiers. The Academy building was promptly evacuated, and remained in Soviet hands for the next 10 days. (Staff members grudgingly accord the troops one compliment: virtually nothing was disturbed during their stay in the building, except for a small stock of whiskey on hand for visiting foreigners. Unfortunately, this had been replenished by the time a *Science* representative was hospitably received for an early morning visit.)

Though many public buildings in Prague were similarly occupied, the fact is that, in the context of Soviet fears over the liberalization of Czechoslovak society, there was a symbolic aspect to the invasion of the Academy, which is not only an honorary and advisory organization on the American style but also the administrative agency for operating some 140 research institutes with over 13,000 employees at various professional levels. For, even prior to the downfall of the restrictive Novotny regime last January, but especially since then, not only the products of scholarly research but also the scholars themselves have been woven into Czechoslovakia's political processes to an extent unknown in the United States and perhaps in any other nation. It is not uncommon for Europeans who hold academic or research positions also to hold national political office, but Czechoslovak scholars have not only held office but have also held considerable power, which is far less common. Ota Sik, director of the Academy's Institute of Economics, was the author of the economic reforms that caused the Soviets to charge that Czechoslovakia was en-