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Magnetically-Excited Flexural Plate Wave Resonator

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ABSTRACT

A flexural plate wave (FPW) resonator was constructed by patterning current lines on a silicon nitride membrane suspended on a rectangular silicon frame. Eigenmodes of the rectangular membrane were excited using Lorentz forces generated between alternating surface currents and a static in-plane magnetic field. The magnetic field strength required for these devices can be achieved with small permanent magnets ($\approx 1 \text{ cm}^3$). Preferential coupling to a particular membrane mode was achieved by positioning current lines along longitudinal mode antinodes. An equivalent-circuit model was derived that characterizes the input impedance of a one-port device and the transmission response of a two-port device over a range of frequencies near a single membrane resonance. Experiments were performed to characterize the effects of varying magnetic field, ambient gas, gas pressure, and input power. To our knowledge, this is the first experimental demonstration of a *resonant* FPW device.

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INTRODUCTION

White and Wenzel have shown that flexural plate waves (FPWs) can be excited in a free-standing membrane formed on a silicon substrate^{1,2}. Included in the layers of their composite membrane are a piezoelectric ZnO layer and interdigital transducers that are used to excite the FPWs. In an alternative approach, Giesler and Meyer have shown that electrostatic excitation can also be used to excite these waves³. Exciting waves in a thin membrane, as opposed to a thick substrate as in a SAW device, results in a lower operating frequency and, consequently, simpler oscillator electronics. In addition, the confinement of acoustic energy in a thin membrane makes the wave velocity more sensitive to surface perturbations, e.g., accumulation of mass. This results in lower detection limits in sensing applications¹.

In this paper we describe a new type of FPW device that uses meander-line current conductors patterned on the membrane surface, in combination with a static in-plane magnetic field, to excite and detect flexural plate waves. These waves are excited in a bounded membrane that acts as a resonant cavity, giving rise to a high-Q response. This results in greater vibrational amplitude for a given input power and greater frequency stability when used in an oscillator circuit. Elimination of the piezoelectric layer simplifies the fabrication and should eventually make FPWs easier to integrate with control electronics.

DEVICE FABRICATION

A schematic view of a magnetically-excited FPW (mag-FPW) resonator is shown in Fig. 1. The mag-FPW is formed by (1) depositing low-stress SiN on both sides of a 100 silicon substrate, (2) patterning a rectangular etch mask opening in the backside SiN layer (aligned with the $\langle 110 \rangle$ crystal planes of the silicon substrate), (3) patterning a meander-line current conductor on the upper surface (centered with respect to the rectangular SiN opening on the backside), and (4) performing an anisotropic Si etch in KOH to remove the silicon below the membrane. This leaves a precisely sized, free-standing rectangular membrane held within a silicon frame with current lines positioned to preferentially excite a particular membrane mode.

Fig. 1 Schematic of the magnetically-excited FPW resonator. Excitation of a rectangular membrane mode is achieved by Lorentz forces generated between an alternating current in a meander-line transducer and a static in-plane magnetic field.

PRINCIPLES OF OPERATION

The operation of the meander-line transducer (MLT) and magnetic field in exciting and detecting FPWs is illustrated in Fig. 1. Current lines, running across the width of the membrane, are positioned at regular intervals along the length of the insulating membrane surface. When a static, in-plane magnetic field is applied perpendicular to the current

direction, a surface-normal Lorentz stress (force per area) $\vec{F} = \vec{J} \times \vec{B}$ is generated, where $\vec{J}$ is the two-dimensional current density on the membrane surface and $\vec{B}$ is the magnetic flux density. The reversing current direction between meander lines causes alternating surface-normal Lorentz forces. Proper positioning of these lines with respect to the membrane boundaries allows excitation of an eigenmode of the rectangular membrane.

The MLT serves to detect membrane resonances as well as excite them. In a one-port device, motion of the MLT in the magnetic field generates an impedance that can be used to track membrane resonance (an emf is induced due to motion of the conductor in the magnetic field). In a two-port device, the membrane resonance excited by forcing an ac current in a first (input) transducer produces motion that generates a voltage on a second (output) transducer.

Referring to the geometry of Fig. 1, the surface-normal membrane displacement u generated by the Lorentz force is described by the equation⁴:

$$D \nabla^4 u - T \nabla^2 u + Z_a \dot{u} + \rho_s \ddot{u} = -B_x J_y \quad (1)$$

where D , T , and ρ_s are the membrane bending moment, tension (force per edge length), and areal mass density, respectively; Z_a is a mechanical impedance arising from fluid loading (gas or liquid). Internal membrane damping can be included by using a complex modulus $E^* = E(1 + j\delta)$, where δ is the loss tangent, in calculating the bending moment.

A rectangular membrane supported at the edges can be excited into a number of

eigenmodes, with displacement given by⁴:

$$u(x,y,t) = A_{mn} \sin(k_m x) \sin(k_n y) e^{j\omega t} \quad (2)$$

where A_{mn} is the complex displacement amplitude; $k_m = m\pi/l$ and $k_n = n\pi/w$, where l and w are the membrane length and width, respectively, and m and n are integers; ω is the angular frequency. Figure 1 shows the membrane being excited into an ($m=6$, $n=1$) mode.

Allowing for the possibility of either one or two MLTs on the membrane (one- or two-port devices), the eigenmode amplitude A_{mn} generated is:

$$A_{mn} = -\frac{2}{j\omega(wl)^{1/2}} \left(\frac{K_1 \hat{I}_1 + K_2 \hat{I}_2}{Z_{mn}} \right) \quad (3)$$

where

$$Z_{mn} = \frac{Dk_{mn}^4}{j\omega} + \frac{Tk_{mn}^2}{j\omega} + j\omega\rho_s + \frac{D\delta k_{mn}^4}{\omega} + Z_a. \quad (4)$$

$\hat{I}_1$ and $\hat{I}_2$ are the current amplitudes in transducers 1 and 2, while K_1 and K_2 are the respective transducer *coupling strengths* to the (m,n) membrane mode. (For a one-port device, $K_2 \hat{I}_2 = 0$.) Z_{mn} is the *mechanical impedance* (ratio of surface-normal stress to particle velocity) associated with exciting the mode, and $k_{mn} = (k_m^2 + k_n^2)^{1/2}$.

Membrane resonances occur at excitation frequencies for which the imaginary part of Z_{mn} vanishes. In a vacuum, where $Z_a = 0$, this occurs at angular frequencies:

$$\omega_{mn} = k_{mn} \left(\frac{Dk_{mn}^2 + T}{\rho_s} \right)^{\frac{1}{2}} \quad (5)$$

At resonance, membrane displacement is maximum, limited only by the loss parameters Z_a and δ .

As mentioned above, the MLT impresses a surface current density $J_y(x,y)$ in a manner designed to preferentially excite a particular membrane mode. The mode coupling factor K_i is proportional to the *spatial correlation* between the current density $J_y(x,y)$ and the (m,n) eigenmode displacement:

$$K_i = \frac{2B_x}{(wl)^{1/2} \hat{I}_i} \int_0^w \int_0^l \hat{J}_y^{(i)}(x,y) \sin(k_m x) \sin(k_n y) dx dy \approx \frac{8B_x N e}{\pi} \left(\frac{w}{l} \right)^{\frac{1}{2}} \quad (6)$$

where $\hat{J}_y^{(i)}$ is the amplitude of current density applied by the i^{th} MLT, N is the number of MLT periods, and e is the coupling efficiency (≤ 1). The approximation indicated in the second expression of Eq. 6 is determined by modeling the current lines as infinitesimally wide and positioned along longitudinal mode (index m) antinodes. This means the meander-line legs are centered at $[\lambda/4 + p(\lambda/2)]$, where λ is the longitudinal mode wavelength (see Fig. 1) and p is an integer. (The coupling efficiency e accounts for the

finite width and imperfect positioning of the MLT lines that occur in practice.) The MLT then couples preferentially to the desired longitudinal mode with minimal coupling to others having non-matching periodicities.

The voltage $V_i = \hat{V}_i e^{j\omega t}$ across an MLT has contributions from ohmic resistance in the line and a back-emf due to motion of the conductor in the magnetic field:

$$\hat{V}_i = \hat{I}_i R_{oi} - \frac{\partial}{\partial t} \int \vec{B} \cdot d\vec{A} = \hat{I}_i R_{oi} + K_i \left(\frac{K_1 \hat{I}_1 + K_2 \hat{I}_2}{Z_{mn}} \right) \quad (7)$$

where i indicates the transducer and R_{oi} is the associated ohmic resistance; the integral is over the "coil" area A (with normal $\hat{x}$) defined by the displaced MLT lines.

From Eq. 7, the MLT voltages (V_1, V_2) and currents (I_1, I_2) near an isolated membrane resonance are related by an impedance matrix:

$$\begin{pmatrix} \hat{V}_1 \\ \hat{V}_2 \end{pmatrix} = \begin{pmatrix} R_{o1} + \frac{K_1^2}{Z_{mn}}, & \frac{K_1 K_2}{Z_{mn}} \\ \frac{K_1 K_2}{Z_{mn}}, & R_{o2} + \frac{K_2^2}{Z_{mn}} \end{pmatrix} \begin{pmatrix} \hat{I}_1 \\ \hat{I}_2 \end{pmatrix} \quad (8)$$

The input impedance for the *one-port* device is then:

$$Z_1(\omega) = \frac{\hat{V}_1}{\hat{I}_1} \bigg|_{\hat{I}_2=0} = R_{o1} + \frac{K_1^2}{Z_{mn}} \quad (9)$$

while the transmission response for the *two-port* device is given by the forward transmission scattering parameter⁵:

$$S_{21} = \frac{2z_{21}}{(z_{11} + 1)(z_{22} + 1) - z_{12}z_{21}} \quad (10)$$

where the z_{ij} in Eq. 10 are elements of the 2 x 2 impedance matrix in Eq. 8, normalized to 50Ω.

From Eq. 8, the electrical characteristics of one- and two-port mag-FPW resonator near an isolated ($m,1$) membrane resonance can be represented by the equivalent-circuit models in Fig. 2. These consist of a parallel LCR resonator that is transformer-coupled to the terminal(s). The parallel membrane elements together represent the mechanical impedance of the membrane mode. From Eq. 4, this impedance has contributions from the membrane bending moment (L_1), tension (L_2), mass density (C_1), internal dissipation (R_1) and fluid loading (L' , R' , and C'). At resonance, the reactive elements (inductances and capacitances) cancel, leaving only a real impedance. Coupling to the membrane mode is represented by an ideal transformer with turns ratio K_1 that depends (Eq. 6) on the number of MLT periods (N) and magnetic field strength (B_x). The mechanical impedance Z_{mn} (with cgs dimensions $\text{cm}^2 \text{ s g}^{-1}$) is transformed (multiplied by K_1^2) and results in an electrical input impedance Z_1 (in ohms) that varies with B_x^2 .

When operated in vacuum, the membrane impedance is determined by the "membrane elements" of Fig. 2:

$$L_1 = \frac{1}{Dk_{mn}^4} \quad (11a)$$

$$L_2 = \frac{1}{Tk_{mn}^2} \quad (11b)$$

$$C_1 = \rho_s \quad (11c)$$

$$R_1 = \frac{\omega}{D\delta k_{mn}^4} \quad (11d)$$

The mechanical quality factor (Q) of the membrane in vacuum can be calculated from the equivalent circuit⁶: $Q = \omega R_1 C_1$. When operated in a fluid (gas or liquid), an additional $L'R'C'$ branch arises; these elements will be defined presently.

Fig. 2 Equivalent-circuit models to describe the electrical response of magnetically-excited FPW resonators in the vicinity of a membrane resonance: (a) one-port device, (b) two-port

device.

Effect of fluid loading Wenzel has shown that FPWs in a membrane generate a flow field (Fig. 3) in a contacting fluid that consists of coupled compressional (surface-normal) and shear (surface-parallel) components⁷. When the FPW velocity is less than the sound velocity in the fluid, this flow field is *evanescent*, confined to within $\lambda/2$ of the surface. With a standing FPW, compressional motion dominates above membrane antinodes; above nodes, shear motion prevails.

Fig. 3 The evanescent flow field generated by a standing membrane FPW in a contacting fluid consists of a superposition of surface-normal and in-plane flow.

The mechanical impedance Z_a associated with exciting the flow field in a contacting fluid is⁷:

$$Z_a \cong N_s \omega^2 \rho \left(\frac{s}{k_m^2 - qs} \right) \quad (12)$$

where N_s is the number of membrane sides contacted by the fluid; $q = k_m [1 - (v/c_c)^2]^{1/2}$ and $s = k_m [1 - (v/c_s)^2]^{1/2}$. In the expressions for q and s , v is the FPW propagation velocity; c_c and c_s are the compressional and shear wave velocities in the fluid. For a Newtonian fluid with density ρ and viscosity η , $s \cong [\omega\eta/(2\rho)]^{1/2}(1 + j)$ so that Z_a can be approximated by series $L'R'C'$ elements defined by:

$$R' = \omega L' = \frac{k_m^2}{2N_s \omega \rho} \left(\frac{2\eta}{\omega \rho} \right)^{\frac{1}{2}} \quad (13a)$$

$$C' = \frac{N_s \rho}{k_m \sqrt{1 - (v/c_c)^2}} \quad (13b)$$

The element C' represents energy stored in the evanescent compressional wave and causes a decrease in the resonant frequency of the FPW resonator given by:

$$\frac{\Delta f}{f_o} = - \frac{N_s \rho}{2k_m \rho_s \sqrt{1 - (v/c_c)^2}} \quad (14)$$

The elements L' and R' arise from shear wave generation in the fluid. Shear fluid motion gives rise to energy storage (L'), while gradients in the shear displacement lead to power dissipation (R') in the viscous fluid. A convenient measure of the fluid-induced membrane damping is the inverse motional resistance contributed by the $L'R'C'$ branch at resonance:

$$\frac{1}{R_2} = \frac{N_s}{1 - (v/c_c)^2} \left(\frac{\omega \rho \eta}{2} \right)^{\frac{1}{2}} \quad (15)$$

RESULTS AND DISCUSSION

Membrane Properties The areal mass density ρ_s of the membrane was estimated from the thicknesses and densities of the SiN layer ($h_1 = 2 \mu\text{m}$, $\rho_1 = 2.95 \text{ g/cm}^3$), Cr metallization layer ($h_2 = 0.015 \mu\text{m}$, $\rho_2 = 7.20 \text{ g/cm}^3$), and Au metallization layer ($h_3 = 0.5 \mu\text{m}$, $\rho_3 = 19.3 \text{ g/cm}^3$). With electrodes $\lambda/4$ wide and positioned at membrane antinodes, the effective areal mass density is estimated at $\rho_s = 1.39 \text{ mg/cm}^2$.

To determine the membrane bending moment D and in-plane tension T , FPW resonators with various transducer periodicities were constructed on the same wafer. Fitting Eq. 5 to the ω -vs.- k data measured for these devices yields D and T for the overall membrane, including SiN and metallization layers: $D = 1.84 \text{ dyne-cm}$, $T = 1.22 \times 10^5 \text{ dyne/cm}$. The latter leads to an in-plane stress (T/h_1) of $6.10 \times 10^8 \text{ dyne/cm}^2$. Using literature values for the bulk SiN Young's modulus and Poisson's ratio, we calculate the bending moment of the SiN layer alone as $D = 1.9 \text{ dyne-cm}$, which is close to the measured value. In addition, the extracted value of the membrane stress is in reasonable agreement with what has been reported for low-stress silicon nitride films.

One-port resonator response Figure 4 shows the impedance response $Z_1(f)$ for a one-port mag-FPW resonator near the (14,1) mode resonance. This device has 7 MLT periods with a periodicity $\lambda = 320 \mu\text{m}$. The SiN membrane dimensions are nominally $l = 7\lambda = 2.2 \text{ mm}$, $w = 10\lambda = 3.2 \text{ mm}$, and $h_1 = 2 \mu\text{m}$. The device has a dc resistance $R_{o1} = 24.98 \Omega$, with a resonance peak that increases with magnetic field strength. In calculating the

impedance response (solid line in Fig. 4) near this isolated membrane resonance, we use Eq. 9 with K_1 given by Eq. 6 and Z_{mn} by Eq. 4. The response is calculated using the measured values of magnetic field strength (B_x) and a constant set of parameters. These include the dc resistance and the membrane parameters T , D , and ρ_s determined above, along with best-fit values for the mechanical damping parameter $R_1 = 1.094 \text{ cm}^2 \text{ s g}^{-1}$ and coupling efficiency $e = 0.26$. The resonant frequency, f_o , is 409.35 kHz. The responses in Fig. 4, measured in vacuum, indicate a *membrane* (mechanical) Q value of 4300. Owing to electrical loading by the input resistance R_{o1} , the *electrical* Q is about 50.

Fig. 4 Impedance response for a single-port mag-FPW resonator for several values of magnetic field strength B_x (points are measured, lines are calculated).

Figure 5 shows a plot of the change in the electrical motional resistance [$Z_1(f_o) - R_{o1}$] vs. magnetic field strength B_x . The line is a power-law fit with a slope of 2.02. From Eq. 9, the motional resistance is proportional to K_1^2/Z_{mn} , with $Z_{mn} = R_1$ at membrane resonance in vacuum. Eq. 6 predicts that K_1^2 , and hence motional resistance, varies as B_x^2 , which is in good agreement with the experimental result: $B_x^{2.02}$.

Fig. 5 Motional resistance vs. magnetic field strength. The power-law fit of 2.02 is in good agreement with the B_x^2 model prediction.

Two-port resonator response Figure 6 shows the transmission response (S_{21}) for a two-port mag-FPW resonator operating in vacuum. A dominant resonant peak is observed at 433.16 kHz, with a resonant insertion loss of 23.9 dB.

Fig. 6 Transmission response (S_{21}) for a two-port mag-FPW resonator operating in vacuum.

The device whose response is shown in Fig. 6 has two MLTs, each having 7 periods with a periodicity of $320 \mu\text{m}$. The spacing between MLTs is 1.5λ . The SiN membrane dimensions are $l = 15.5\lambda = 4.96 \text{ mm}$, $w = 10\lambda = 3.2 \text{ mm}$, and $h_1 = 2 \mu\text{m}$. In Fig. 6 the points are measured values while the line is calculated from Eq. 10 (z_{ij} from Eq. 8, K_i from Eq. 6, and Z_{mn} from Eq. 4) using the measured value of magnetic field strength ($B_x = 4.64 \text{ kG}$) and the membrane parameters determined above. The MLT parameters determined by fitting the data (measured in vacuum) include $R_1 = 1.90 \text{ cm}^2 \text{ s g}^{-1}$, $e = 0.22$, and $\rho_s = 1.37 \text{ mg/cm}^2$. The membrane Q for this device operating in vacuum is 7060. The MLT efficiencies for the two-port resonator (22%) are comparable to those of the one-port resonator (26%).

Figure 7 shows the variation in resonant insertion loss with magnetic field strength for this two-port mag-FPW resonator. The points are measured values, while the line is calculated from the model. In this plot, insertion loss (in decibels) varies linearly with $\log(B_x)$ for B_x below about 4.3 kG. In this regime, insertion loss varies approximately

38.7 dB per decade of magnetic field strength. For weak transducer coupling, the coupled energy into and out of the membrane is expected to vary as B_x^2 (from the one-port model). This would give a transmission variation of 40 dB per decade of magnetic field strength, close to what is observed. At higher field strengths or coupling levels, the ports load the membrane resonance, and insertion loss decreases less rapidly with increasing field strength. The linear model captures some of this incremental reduction; nonlinear effects associated with amplitude stiffening may account for the remainder.

Fig. 7 Insertion loss at resonance vs. magnetic field strength for a two-port mag-FPW resonator operating in vacuum.

Gas Loading For the 2 μm -thick SiN membrane used, the FPW velocity ($v = 1.3 \times 10^4$ cm/s) is lower than the sound velocity in the gases tested. This leads to excitation of an evanescent displacement field (Fig. 3) in the gas next to the membrane surfaces. At a resonant frequency of 400 kHz in nitrogen, the decay length is approximately 78 μm for this evanescent field.

Figure 8 shows the fractional change in resonant frequency ($\Delta f/f_0$) vs. pressure for a one-port mag-FPW resonator in several gases. The decrease in resonant frequency is due mainly to gas entrainment by the evanescent compressional component of displacement. From Eq. 14, this is expected to vary with gas density ρ which is proportional to pressure.

Fig. 8 Fractional change in resonant frequency vs. pressure for a one-port resonator in several gases, showing the effect of gas entrainment by the evanescent field (Fig. 3).

Figure 9 shows the variation in inverse motional resistance ($1/R_2$), a measure of membrane damping, with pressure for several gases. The points are measured; lines are linear least-squares fits to the data. The damping arises from viscous dissipation occurring above membrane antinodes where there is a significant gradient in shear displacement. Eq. 15 predicts damping will vary as $(\rho\eta)^{1/2}$, as is found with thickness-shear mode resonators operating in a Newtonian fluid⁸. Since gas density ρ varies with pressure while viscosity η is relatively constant over this range of gas pressures, $1/R_2$ varies as the *square root* of pressure. On average, the calculated damping due to gas loading is about 15% less than what was measured. This is most likely due to the *radiation* of compressional waves at the membrane edges; this arises from the finite extent of the membrane and was not included in the damping model.

Fig. 9 Change in inverse motional resistance ($1/R_2$) vs. square root of pressure for a one-port resonator in several gases. The $P^{1/2}$ dependence arises from viscous damping due to in-plane fluid motion (Fig. 3).

SUMMARY

Flexural plate wave resonators have been constructed using bulk micromachining techniques to form a free-standing silicon nitride membrane supported by a silicon frame.

High-order eigenmodes, e.g. (14,1), can be excited in the rectangular membrane using Lorentz forces. These are generated by surface currents defined by a conductor pattern on the membrane surface in combination with a static in-plane magnetic field.

Efficient coupling to a membrane mode occurs when the current lines are positioned at the longitudinal mode antinodes and alternate in direction every half wavelength. This leads to a meander-line transducer geometry. This transducer couples preferentially to a particular longitudinal mode ($m,1$).

At resonance, membrane motion becomes significant. MLT movement in the B-field induces a voltage on the MLT. For a one-port device, this causes an impedance response. For a two-port device, it generates a voltage on the output transducer. These responses have been modeled and the model gives good agreement with experiment in predicting impedance and transmission (2-port device) vs. frequency, magnetic field, and gas pressure.

Several applications are anticipated for the mag-FPW resonator. The low areal mass density of the membrane makes it extremely sensitive to surface mass accumulation. Hence, addition of a chemically sensitive film should allow sensitive chemical detection. Since the limit of detection is determined by the mass sensitivity of frequency ($\Delta f/\Delta \rho_s$) divided by the frequency uncertainty (oscillator fluctuation), a useful figure of merit⁹ for resonant sensors is $Q (\Delta f/\Delta \rho_s)$. The relatively high Q of the FPW resonator, combined with its high mass sensitivity, give it a high figure of merit.

The mag-FPW resonator is also suitable for other sensing applications. The device can be made very sensitive to changes in membrane tension. This leads to nonlinear (amplitude-stiffened) responses at higher drive levels¹⁰, but also makes the device sensitive to other environmental influences that affect membrane tension, such as temperature, differential pressure, and strain.

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Fig. 4

Figure 8 Equivalent-circuit models to describe the response of magnetically-excited

FPW resonators in the vicinity of a membrane resonance: (a) one-port

device, (b) two-port device.

file:Figure24.JNB

Fig. 3

$f_0 = 409.35$ kHz

file:Figure18.jnb

Do 5 4

Fig. 5

file:Figure12.jnb

Fig. 26

Fig. 1

Fig. A 8

ok as is

FOA

Fig. 9