RESONANT M/NEMS PIEZORESISTORS FOR NARROW-BAND ELECTRONIC AMPLIFICATION

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ABSTRACT

This work demonstrates amplification of electronic signals using a bare silicon electromechanical resonant micro-device. The structure consists of a narrow piezoresistor connecting two plates that can vibrate in an in-plane resonant mode. It is shown that vibration amplitude amplification by a combination of mechanical quality factor and thermal-piezoresistive “energy pumping” can turn the relatively weak piezoresistivity of silicon into a viable amplification mechanism. The energy pump is a result of interactions between electro-thermal forces in the piezoresistor and its piezoresistivity leading to a negative electrical equivalent resistance for the device (i.e. an active element). Tunable voltage gains up to 16dB for a 50Ω load have been demonstrated at 4.8MHz. The thermal-piezoresistive coupling also significantly enhances the effective quality factor (Q) of the resonator showing Q of up to 204,000 for a structure with intrinsic mechanical Q of less than 15,000 in air. Such narrow band amplifiers can potentially be used as channel selective low-noise amplifiers in wireless communications eliminating the need for multiple off-chip filtering steps.

INTRODUCTION

Transistors have been the basis of modern electronics propelling the microelectronics industry towards unimaginable triumphs over the past few decades. Although the solid state transistor technology has been an effective and reliable power-house leading the human civilization into the electronics age, it seems to have reached its fundamental limits while the quest for more versatile next generation technologies continues. One of the needs not addressable using the semiconductor based technologies is the need for ultra-narrow band filtering along with amplification of small signals in wireless communications and some sensory applications. Due to the relatively low quality factor of on-chip inductors and capacitors, accurate and narrow-band frequency selection still relies on off-chip mechanical resonators. Even such mechanical components cannot offer high enough selectivity for most wireless applications necessitating further filtering for selection of individual channels after frequency down-conversion.

MEMS resonators have been the center of attention over the past two decades in hopes of enabling on-chip frequency selection. The “Resonant Gate Transistor” demonstrated in 1967 [1], known to be the very first MEMS resonator, was an active device integrating high mechanical Q of a suspended metallic cantilever within a field effect transistor. However, the main bulk of recent research on micromechanical resonant devices has been focused on piezoelectric and capacitive resonators that are passive components. Such devices have not been able to meet the selectivity and pass-band loss requirements for wireless communications leading some researchers to turn the focus back to active on-chip resonant components. Examples of such include the resonant amplifier utilizing capacitive actuation and piezoresistive readout [2], and the resonant beam selectively doped for field effect transduction (similar to a FET) [3]. This work takes such efforts one step further by taking advantage of the previously demonstrated internal thermal-piezoresistive energy pumping [4,5] to reach significantly higher amplification factors using extremely simple devices. In

addition to frequency selection capability, such devices can be aggressively scaled down into the deep nano-scale range without hitting some of the fundamental road blocks that the semiconductor industry is facing.

CONCEPT AND THEORETICAL ANALYSIS

A piezoresistor is an active transducer by nature as it can absorb electrical power from a DC source and transfer a modulated power to a load. Similar to the current flow in a transistor channel that is controlled by an input gate or base voltage, current in a piezoresistor is controlled by its mechanical stress. Therefore, an electrical component very similar to a transistor can be realized by combining a piezoresistor with an electromechanical actuator turning the input voltage into a mechanical force. The piezoresistive effect, however, is generally far too weak for such “transistor” to be able to offer a useful amplification factor (gain > 1). For example, while the current in a solid state transistor can be modulated over its full range by only a fraction of a volt change in its input voltage, 1MPa of mechanical stress changes the current in a silicon piezoresistor by less than 0.1%.

One solution to make up for this weakness is to use mechanical resonance to multiply vibration amplitude and therefore mechanical stress resulting from the input force by Q times. In this manner, a piezoresistor embedded within a high-Q resonant system can offer significantly improved electrical amplification behavior. Voltage gain as high as 4.6 dB has been demonstrated in [2] using this approach. This work takes this one major step further by adding the thermal-piezoresistive internal amplification effect [4,5] that can further amplify the resonator vibration amplitude and consequently the piezoresistor amplification factor at resonance. For this purpose, instead of using an electrostatic actuator to turn the input voltage to mechanical strain, the piezoresistor itself is used as a thermal actuator. Figure 1 schematically shows how such device operates as a self-amplifying resonator by coupling of thermal actuation forces with piezoresistivity of the actuator. The combination of DC bias current and input AC signal leads to slight temperature fluctuations (via Joule heating) and therefore thermal stress at the same frequency as the input signal within the piezoresistor. If the input signal frequency is close to the natural resonant frequency of the vibration mode of interest, the mode is excited leading to a significant vibration amplitude and therefore fluctuating strain in the same piezoresistor. The resulting strain in turn modulates the electrical resistance of the piezoresistor that along with the DC bias current leads to an additional fluctuating ohmic heating component. Depending on the sign of the piezoresistive coefficient of the structural material this additional heat (and therefore force/stress) component can be in phase or out of phase with respect to the main heat component resulting from the input signal. It can be demonstrated that for n-type silicon, where the piezoresistive coefficient is negative, the piezoresistive heat component will be in phase with the input signal heat component and therefore can add to the resonator vibration amplitude [5]. In this manner, the piezoresistor absorbs more energy from the DC bias source and amplifies the mechanical vibration amplitude and along with it the stress and therefore voltage fluctuations across the piezoresistor (resonant amplifier output voltage).

Figure 1. Schematic diagram of an amplifying resonant piezoresistor showing the internal thermo-electromechanical amplification loop, also known as the internal energy pump [5].

Figure 2 shows the SEM view of the silicon structure used in this work. The device consists of a narrow piezoresistor in the middle connecting two plates that can vibrate in-plane in opposite directions in the resonant mode of interest.

Figure 2. SEM view of the silicon microstructure used as an electronic amplifier consisting of a $9\mu\text{m} \times 600\text{nm}$ piezoresistor and two resonating plates. The structure is $4\mu\text{m}$ thick.

The amplitude of the pumped energy can be tuned by changing the bias current of the resonator. When the pumped energy is smaller than the energy lost due to mechanical losses compensating only a portion of resonator mechanical loss, the resulting effective Q of the resonator increases and can reach values much higher than the intrinsic mechanical Q of the device. This is referred to as thermal-piezoresistive Q -amplification [5]. By further increasing the feedback loop gain at some point the pumped energy can compensate all the mechanical energy loss in the system leading to self-sustained oscillation [5].

Fig. 3a shows the equivalent electrical circuit of such thermally actuated resonant piezoresistor [6]. R_A represents the physical resistance of the piezoresistor at rest, which is in parallel with a series RLC representing the resonance behavior of the device. The current passing through the RLC represents the motional current of the resonant structure, i.e. the modulated bias current due to vibration induced piezoresistor fluctuations. The motional conductance of the device, which is the ratio of motional current to the actuation voltage is given by Eq. (1), where α , E , and π_l are the thermal expansion coefficient, young's Modulus, and longitudinal piezoresistive coefficient of the structural material respectively, C_{th} is the thermal capacitance of the thermal actuator (piezoresistor), ω_0

is the mechanical resonance frequency, and I_{dc} is the bias current. [6]

$$g_m = \frac{\alpha E \pi_l Q I_{dc}^2}{C_{th} \omega_0} \quad (1)$$

Figure 3b shows a simplified version of the same circuit at resonance frequency consisting of the physical resistance (R_A or the passive resistance) in parallel to a current source. The direction of the current from the current source can be the same or the opposite of the direction of the current in the resistor depending on the sign of the piezoresistive coefficient. An opposing current source can be interpreted as a negative resistor with value of $1/g_m$.

Figure 3. Small signal equivalent circuit of the a resonant piezoresistive amplifier: (a) the RLC combination representing resonant behavior of the device, (b) the RLC simplified to a dependent current source (potentially negative resistance) at resonance frequency.

Operation of such devices in both Q -amplification and self-oscillation modes have previously been demonstrated and analyzed [5]. This work demonstrates that such devices can in fact have three distinct modes of operation when a significant resistive load is added to the output of the device. The resistive load adds an electrical loss component to the equation delaying the onset of self-oscillation. It can be shown that in this case in the interval between full compensation of resonator losses and the onset of self-oscillation, electrical amplification occurs delivering the amplified input signal to the load. Therefore, depending on the value of bias current, the piezoresistor can operate in three different regimes: attenuation, amplification, and self-sustained oscillation. At small bias currents g_m has a very small negative value, therefore the $1/g_m$ resistor is very large and the overall resistance of the device R_D (where $R_D = R_A || 1/g_m$) is positive acting as a passive resistance consuming a part of the input power and attenuating the input signal.

As the bias current is increased, absolute value of g_m increases, which in turn decreases the absolute value of the active resistance. When the value of the active resistance matches the value of the passive resistance, R_D is no longer positive. In this case the resonator acts as an overall negative resistance in series with the load and no longer attenuates the input signal by consuming power, but rather adds power to the system increasing the power delivered to the load. Gain of the system in this case can be calculated by:

$$\text{Gain} = \frac{R_L (1 + g_m R_A)}{R_A + R_L (1 + g_m R_A)} \quad (2)$$

where R_L is the load resistance. This gain is only valid for bias currents at which the self-sustained oscillation has not yet occurred. Once the self-oscillation starts, the output signal will no longer depend on the input signal and input to output gain becomes meaningless.

Finally, self-sustained oscillation starts when the value of g_m becomes so high that the overall combined device and load resistance becomes negative. In other words, this occurs when the

absolute value of g_m reaches the conductance of the parallel combination of the load and piezoresistor physical conductance ($R_L^{-1} + R_A^{-1}$), and therefore, the gain from Eq. (2) goes to infinity. With larger load resistance values, the transition from amplification to self-sustained oscillation occurs at lower bias currents. Therefore, for general application of such amplifier, the matched value of the load resistance must be chosen wisely and according to the maximum gain requirements.

Figure 4. Qualitative representation of overall resistance of the device (R_D) versus bias current, showing three different working regions and transition points between them.

EXPERIMENTAL RESULTS

The thermal-piezoresistive resonator shown in Fig. 2 was fabricated through a single mask fabrication process on an N-type SOI substrate with device layer thickness of 4 μm . Submicron piezoresistor width was achieved by thinning down the lithography defined beam via oxidation and oxide removal. The measurement configuration used for characterization of the device is shown in Fig. 5. The 50 Ω resistors are network analyzer port input resistances that need to be considered in gain calculations. R_1 and R_2 were included in the measurement circuit so that input and output termination resistance of the device can be controlled.

Figure 6. Measured frequency responses of the device with different DC bias values. As the bias voltage (and current) increases the peak amplitude increases while sharpening (Q enhancement) and the device goes from an attenuator to an amplifier, and eventually self-sustained oscillation occurs.

Fig. 6 shows the measured frequency responses taken from the Network Analyzer that show the gain at resonance frequency as a function of bias voltage, with R_1 and R_2 set to zero, and the input power set to -45 dBm. As discussed in the previous section, by increasing the bias current the resonator effective quality factor increases, making the peak sharper and taller. By passing the attenuation region the peak's value, which is the voltage gain at resonance, becomes positive. As the current is increased, Joule heating also increases, and the resulting temperature increase will cause a resonance frequency shift due to changes in the piezoresistor stiffness [7].

Figure 5. (a) Test circuit configuration showing bias resistors and coupling capacitors. Effectively, the MEMS device is connected in series with the input resistance of the network analyzer acting as a 50 Ω load. (b) Combining the effects of Network Analyzer impedances with the circuit resistances to treat the whole device and its supporting elements as a two port network.

With a constant input termination resistance, i.e. the same input power, according to Eq. (2), increasing the load resistance should increase both gain and voltage swing. However, since higher gain takes the device closer to mechanical saturation, the input power needs to decrease, which results in reducing the output voltage swing. By choosing the right values for R_1 and R_2 one can control both gain and voltage swing. The experimental results showing the relationship between gain, voltage swing, and input/output termination resistances ($R_{T1}=R_1+50$ and $R_{T2}=R_2+50$) are graphed in Figures 7 and 8. Therefore, voltage gain and swing of the amplifier, can be tuned by changing the values of R_1 and R_2 and bias current. It should be noted that all the measurements have been performed under atmospheric pressure and therefore vacuum packaging would not be required in a real application.

Figure 7. (a) Measured voltage gain with different input and output termination resistances, (b) measured output voltage swing with different input and output resistances.

CONCLUSION

Amplification of electronic signals using a bare silicon electromechanical resonant micro-device with tunable gain, swing and frequency was demonstrated. It was demonstrated that thermal piezoresistive resonators in combination with resistive loads can work in three different regimes of attenuation, amplification, and self-sustained oscillation.

Such devices can potentially address the need for low loss highly selective on-chip frequency selection in communication systems.

Figure 8. Output voltage and swing as a function of input termination resistance with a constant output termination resistance, showing the tunability of the gain and output swing of the MEMS resonant amplifier ($R_{T2} = 50 \Omega$).

Future work includes better understanding and improvement of the device gain and power handling (output voltage swing) limitations.

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