

A Generic Micromachined Silicon Platform for Low-Power, Low-Loss Miniature Transceivers

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Abstract

A generic micromachined silicon platform for low-power, low-loss miniature transceivers is described. This platform is fabricated by the dissolved wafer process and supports: 1) high self-resonant frequency and quality factor inductors suspended on a dielectric diaphragm, 2) low-loss polysilicon-metal capacitors, and 3) polysilicon resistors. The process uses a deep boron diffusion step to create silicon anchors which support a stress compensated dielectric diaphragm. The platform can be used to build miniature transmitters using either a hybrid-attached surface-mount transistor, or flip-chip bonded RF circuit. A Colpitts oscillator transmitter (5 mm x 5 mm area) with a two turn dielectric suspended inductor was designed and fabricated using this technique. The transmitter oscillates in the frequency band of 275-375 MHz, consumes 200 μ A, and has a transmission range of \sim 3 feet. The suspended coil has an inductance of 115 nH, a self-resonant frequency of $>$ 750 MHz and a Q of 22 at 275 MHz.

Keywords: Transmitter, Transceiver, Coils.

Introduction

Wireless integrated microsensor systems for military, manufacturing, biomedical, security, transportation, and environmental monitoring applications are in high demand [1,2]. Low-power bi-directional transceivers are one of the central components of these emerging microsystems. Integrated inductors with high self-resonance frequency and quality factor are essential components in low-power and low-phase noise transmitters. The limiting factors in achieving these parameters for inductors fabricated on silicon are: substrate and metal series resistance loss (limiting the Q), and parasitic capacitance to the substrate (reducing the self-resonance frequency and the Q). Various techniques have been used to reduce the substrate loss and parasitic capacitance (by selectively removing the substrate under the inductor) [3], or series resistance (multi-level metallization and electroplating) [4-6]. Incorporating these techniques into integrated circuits requires added process complexity associated with multi-level metallization, front-side etching which is dependent on crystal orientation, and added area. In this paper we present the development and application of a generic micromachined silicon platform that supports high self-resonance frequency and quality factor inductors and low-loss capacitors and resistors on suspended dielectric diaphragms.

Figure 1 shows the micromachined silicon platform mounted on a glass back-plate for mechanical support. This platform can be used to build miniature transceivers, either stand-alone to support hybrid attached surface-mount transistors, or flip-chip bonded to RF circuits on an integrated chip, thus saving valuable chip area. The platform has been used to design and implement a Colpitts oscillator which is switched on-and-off by a 1 Mbps incoming digital data in a PCM format. All the passive components are fabricated on the silicon substrate and the only active element (Motorola RF transistor MRF931) is connected to the substrate. The platform is fabricated by the dissolved wafer process. After creating the silicon support anchors, a dielectric diaphragm is deposited and various components (electroplated inductor, metal-polysilicon capacitor, and polysilicon resistor) are placed on it. At the end, the silicon substrate is etched, leaving anchors and dielectric suspended passive elements. The capacitive parasitics associated with the surface mount device pads can also be minimized by suspending them on the diaphragm. This technique is simple, saves area, alleviates the need for front-side etching, and does not require multi-level metallization.

Components Design and Models

In order to accurately design and predict the behavior of various passive components, lumped-element circuit models were used. Figure 2 shows the physical models used to design the inductor and capacitor [5, 7]. The inductor is modeled by: L_s representing the low-frequency series inductance, R_s representing the series resistance having a frequency dependence related to the skin effect and other high frequency effects, C_o modeling the fringing capacitance between the turns, C_{ox} is the capacitance from the metal layer to the substrate, and finally R_{sub} and C_{sub} represent the substrate resistance and capacitance respectively. Removing the semiconducting substrate from underneath the inductor drastically reduces the effects of C_{ox} , C_{sub} , and R_{sub} . Therefore one needs to optimize the values of L_s , R_s , and C_o in order to achieve the required self-resonance frequency and quality factor. Equations 1-3 were used to calculate the low-frequency inductance of an air-core rectangular planar inductor [8].

$$k_1 = L_{coil} \log(L_{coil} + \sqrt{L_{coil}^2 + W_{coil}^2}) \quad (1)$$

$$k_2 = W_{coil} \log(W_{coil} + \sqrt{L_{coil}^2 + W_{coil}^2}) \quad (2)$$

$$L_{coil} = 9.21 \times 10^{-9} n_r^2 (L_{coil} + W_{coil}) \log\left(\frac{8L_{coil}W_{coil}}{n_r w_r + n_r h_r}\right) - k_1 - k_2 \quad (3)$$

In these equations, all dimensions are in centimeters, the inductance is in Henry, n_r is the number of turns, w_r is the width of each turn, h_r is the electroplating height of the coil turns, L_{coil} is the effective length, and W_{coil} is the effective width of the coil. The series resistance R_s includes the DC and a frequency dependent component. The DC component can be designed by a knowledge of the coil dimensions and metal resistivity ($\rho_{Gold} = 2.05 \times 10^{-8}$.m). The frequency dependent component has to account for the skin effect (Equation 4), and magnetic fields. The combined effects can be modeled by Equation 5, [9].

$$= \sqrt{\frac{2}{\mu}} \quad (4)$$

$$R_s = \frac{\rho l}{w (1 - e^{-\frac{l}{d}})} \quad (5)$$

where ρ is the resistivity, l is the length, w is the line width, and d is the metal skin depth. The fringing capacitor between the electroplated turns determines the resonant frequency and can be calculated by using Equation (6), [10]. In this equation t is the metal thickness, w is the spacing between the lines, d is the adjacent lines center-to-center distance, and ϵ_{eff} is the effective dielectric constant ($\epsilon_{eff} \sim 1$ for $d/h \gg 1$, and $\epsilon_{eff} = (1 + \epsilon_r)/2$ for $d/h \sim 1$).

$$\frac{C}{l} = \frac{27.8 \epsilon_{eff}}{\ln \frac{(d-w)}{w+t} + 1} \quad (pF/m) \quad (6)$$

The metal-polysilicon capacitor is modeled by C_0 representing the low frequency capacitance, R_p representing the dielectric leakage, R_s representing the series resistance, and C_{sub} modeling the capacitance from the polysilicon bottom electrode to the silicon substrate. The effect of C_{sub} is reduced drastically by removing the substrate and the series resistance is determined by the polysilicon sheet resistance. The leakage resistance is very high due to the quality of the LPCVD oxide used as a dielectric layer. All the values for the capacitor circuit model can be derived easily and the dissipation factor can be calculated ($D = \frac{1}{R_p C_0}$).

Using the above formulae an integrated inductor was designed as part of the Colpitts transmitter, Figure 3. The integrated coil has 2 turns, each 25 μ m wide, 5 μ m thick, and separated by 25 μ m. It is suspended on diaphragm patches 0.3x1.8 mm in dimensions and was designed for an inductance of 110 nH, a self-resonance frequency of 750 MHz, and a quality factor of ~ 18 at 275 MHz. The tuning capacitor C_1 can be laser trimmed between 1-4 pF to set the transmission frequency to any value between 275-375 MHz. The resistance R sets the

quiescent current drain of the transmitter and is 11.5 K (200 μ A current with a 3 V driving voltage).

Fabrication Process

Figure 4 shows the fabrication sequence of the silicon platform. The process starts with a deep boron diffusion step (1175 $^{\circ}$ C for 7 hrs + 1200 $^{\circ}$ C drive-in for 5 hrs) to form the support anchors (10 μ m) for the substrate. This is followed by the deposition of a stress relieved LPCVD dielectric sandwich layer $SiO_2(4000\text{\AA})/Si_3N_4(2000\text{\AA})/SiO_2(4000\text{\AA})$ which will form the membrane over which the integrated coil and transistor mounting pads are suspended. Next a polysilicon layer is deposited and patterned to define the resistor and the bottom plate of the capacitors. The capacitor dielectric LPCVD oxide (~ 5000 \AA) is then deposited and contacts are opened to the polysilicon layer. A $Cr(400\text{\AA})/Au(3000\text{\AA})/Cr(200\text{\AA})$ electroplating seed layer is then deposited followed by patterning a thick photoresist (PR4620, spin at 2500 rpm, 250 sec exposure time, 8 minutes development, ~ 9 μ m thickness) mold layer. The coil and top capacitor plates are electroplated (55 $^{\circ}$ C plating bath, 2 mA/cm² current density) and seed layer is etched after removing the resist mold. Finally the wafer is etched in Ethylene Diamine Pyrocatechol (EDP) [11] and individual dies are separated. The dies are attached to a glass back-plate for mechanical protection and the RF transistor is mounted on the gold plated pads with silver epoxy. The micromachined platform is rugged and its fabrication does not depend on the silicon crystal orientation for selective substrate removal. It can support active hybrid components while reducing the large capacitances associated with their bond pads by suspending them on dielectric diaphragms. Figure 5 shows a SEM of a transmitter chip with electroplated coil and surface mount RF transistor.

Experimental Results

Important parameters for various passive components were measured with an impedance analyzer. Table 1 summarizes the measurement results for integrated coil and capacitor which show good agreement with the designed values.

Table 1: Measurement results for integrated coil and capacitor.

Component	Designed	Measured
Coil		
L_o	110 nH	115 nH
R_s (DC)	6.5	7
Q (at 275 MHz)	18	22
f_{rs}	> 750 MHz	> 750 MHz
Capacitor		
C_o /Area	6.9×10^{-9} F/cm ²	6.9×10^{-9} F/cm ²
R_p	---	> 20 M
Dissipation Factor	---	< 5×10^{-3}

After all passive elements were characterized, a surface mount RF transistor was mounted on the substrate with silver epoxy and the transmitter was operated with a 3 V battery.

Figure 6 shows the spectrum of the received voltage using a wire antenna connected to a spectrum analyzer. As can be seen the oscillation frequency is at 272 MHz with a very sharp peak indicating the low-phase noise achieved by using a high Q inductor. The transmitter consumes $\sim 200 \mu\text{A}$ of current which can be further reduced by increasing the emitter resistance. The transmission range was measured to be ~ 3 feet and the reception showed characteristics associated with using a loop transmitting antenna (the received voltage drops on top of the coil and increases by moving away in side directions). The inductor Q was calculated to be ~ 22 from the received voltage spectrum which is slightly more than the designed value. This is due to the over-estimation of the skin effect at 275 MHz by using Equation 5.

Conclusion

We have developed a generic micromachined silicon platform for low-power, low-loss miniature transceivers. This platform is fabricated by the dissolved wafer process and supports: 1) high self-resonant frequency and quality factor inductors suspended on a dielectric diaphragm, 2) low-loss polysilicon-metal capacitors, and 3) polysilicon resistors. By suspending an electroplated coil on a dielectric diaphragm we were able to increase the self-resonance frequency and quality factor of the inductor without using multilevel metallization and front side selective substrate removal which adds process complexity. The platform was used to build miniature Colpitts transmitter by a hybrid attached surface-mount transistor. The transmitter consumes $200 \mu\text{A}$, has a range of ~ 3 feet, and uses a two turn coil with an inductance of 115 nH and a Q of 22 at 275 MHz. Various passive components for a low-power command receiver were also included in the substrate design. The receiver part will be connected to a custom designed IC for external control of the data acquisition circuitry (power saving, gain setting, etc.).

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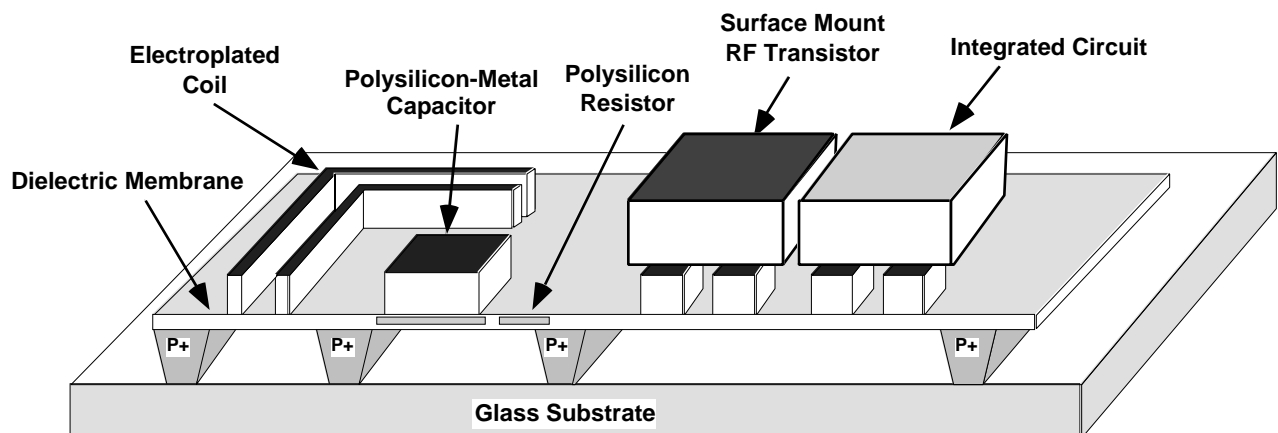


Figure 1: Micromachined silicon platform with surface mount RF transistor, RF integrated circuit, and glass back plate support.

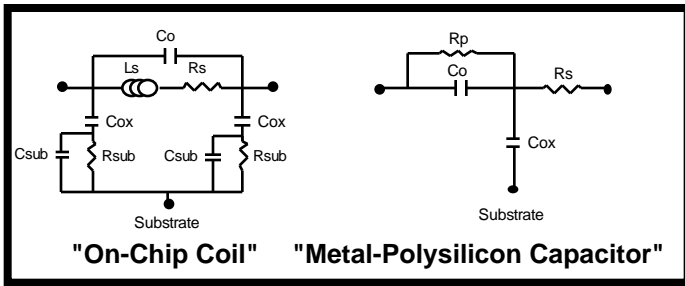


Figure 2: Lumped element circuit model for an inductor and a metal-polysilicon capacitor.

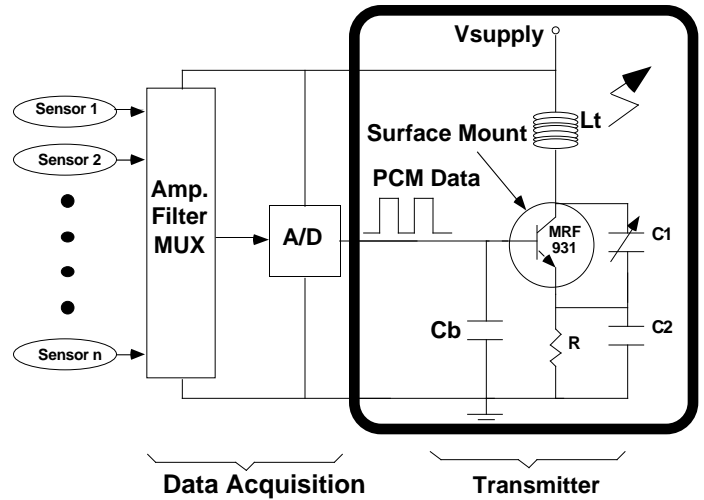


Figure 3: An instrumentation microsystem with a Colpitts transmitter.

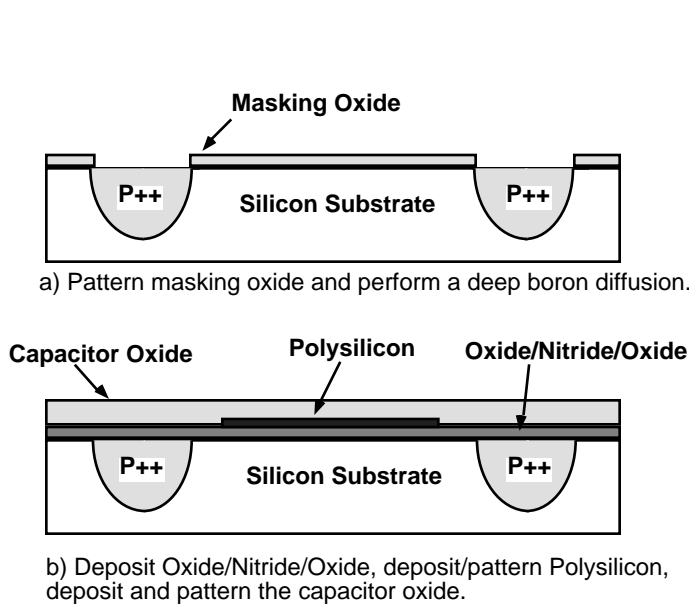
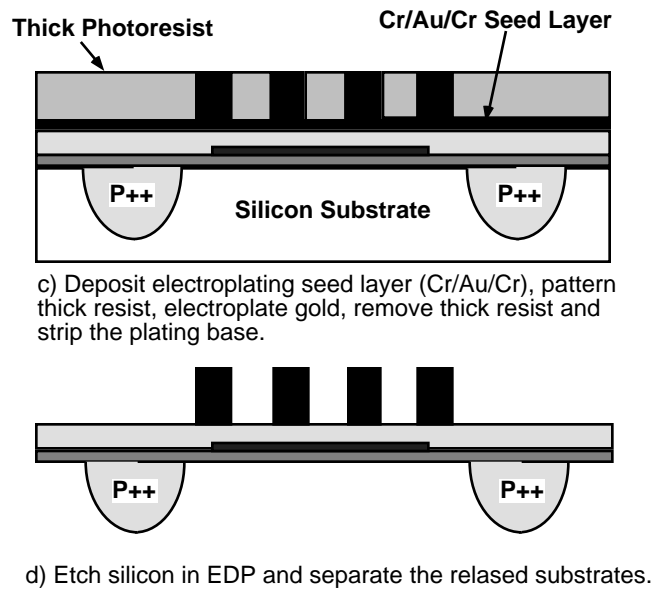


Figure 4: Cross section of the transmitter platform fabrication sequence.



d) Etch silicon in EDP and separate the released substrates.

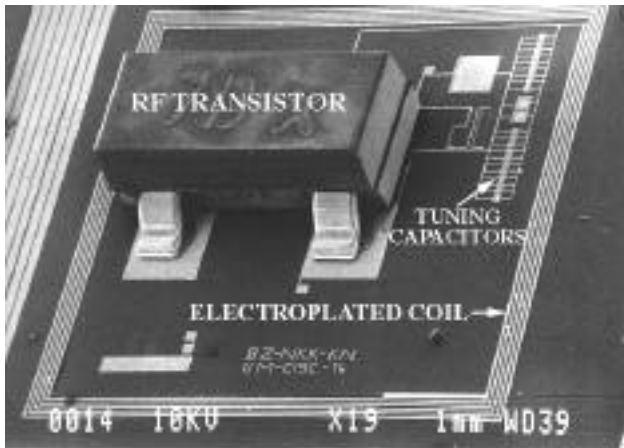


Figure 5: SEM of a transmitter platform with surface mount RF transistor.

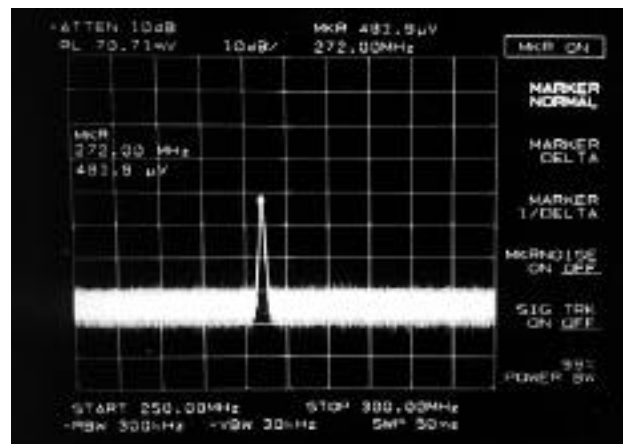


Figure 6: The received signal spectrum of the Colpitts transmitter.