

A PACKAGED MICROMACHINED SWITCHED TUNABLE INDUCTOR

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ABSTRACT

A new implementation of micromachined switched tunable inductors using transformer action and electrostatically-actuated switches is presented. The inductors and the micromachined ohmic switches are made of silver (Ag) to minimize the resistive loading on the effective inductance and achieve large tuning and high quality factor (Q). The presented tunable inductor is packaged using a low-cost wafer-level polymer packaging technique and shows no degradation in quality factor after packaging.

INTRODUCTION

Tunable inductors can find applications in tunable filters, voltage controlled oscillators, and reconfigurable impedance matching networks, especially when a wide frequency tuning is desired. Both discrete and continuous tuning of inductors using micromachining techniques have been reported in the literature. Discrete tuning of inductors is usually achieved by adding segments to the inductor length using integrated switches [1]. However, the incorporation of micromechanical switches into the body of the inductor would reduce the inductor quality factor. Alternatively, continuous tuning of inductors is realized by displacing a magnetic core [2,3] or using movable structures with large traveling range [4,5], which make the integration and packaging of the inductors difficult.

In this paper, we present a new implementation of tunable inductors using micromachined electrostatically-actuated silver switches. We use silver as the structural material since it has superior electrical and mechanical properties compared to the other metals. We employ a wafer-level polymer packaging technique to encapsulate the tunable inductor. Using the presented method, a 1.01nH silver tunable inductor is switched to four discrete values and achieves a maximum tuning of 40% at 5GHz. This inductor exhibits a decent embedded Q of 45 at 5GHz and shows no degradation in Q after packaging. The switched tunable inductor presented here outperforms the reported tunable inductors in term of its high embedded quality factor at high frequencies.

DESIGN

Figure 1 illustrates the switched tunable inductor concept. The inductance is taken from port one and a plurality of coils at port two are switched in and out (two inductors in

this case). When both switches at port 2 are open, the inductance seen from port 1 is L_1 . The two coils at port 2 have different sizes and hence have different mutual inductance effect on port one when switched on. As a result, the effective inductance of port 1 can have four discrete values depending on which coil at port 2 is switched on. The equivalent inductance and resistance seen from port 1 are found from:

$$L_{eq} = L_1 \left(1 - \sum_{n=2}^3 \frac{b_n k_n^2 L_n^2 \omega^2}{R_n^2 + L_n^2 \omega^2} \right) \quad b_n = 0 \text{ or } 1 \quad (1)$$

$$R_{eq} = R_1 + \sum_{n=2}^3 \frac{b_n R_n k_n^2 L_1 L_n \omega^2}{R_n^2 + L_n^2 \omega^2} \quad (2)$$

where L_n is the inductance of the secondary coils; R_n represents the sum of the series resistance of each secondary coil and the contact resistance of its corresponding switch; k_n is the coupling coefficient; b_n represents the state of the switch and is 1 (or 0) when the switch is on (or off). To achieve maximum tuning, R_n should be much smaller than the reactance of the secondary coil ($L_n \omega$), as shown in (1), which requires high Q inductors and low contact resistance switches that is best implemented using micromachining technology. In this work, high Q inductors and ohmic switches are made of silver using micromachining techniques and the switches are actuated by applying a DC voltage to port 2.

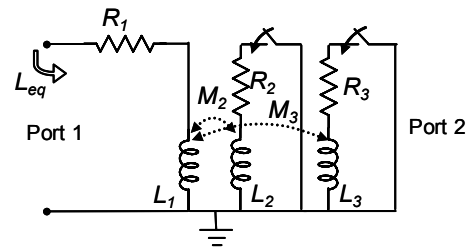


Figure 1. Switched tunable inductor electrical model.

Figure 2 shows SEM view of a switched tunable silver inductor. The two coils at port 2 are in series connection to a vertical ohmic switch through a narrow spring. Springs are designed to have a small self-inductance and stiffness <15N/m. The actuation voltage of the switch is 40V. The close up view of the switch pad with actuation gap of 3.8 μ m is shown in Fig. 3. The actuation voltage of the switches can be reduced to less than 5V by reducing the gap size to ~0.9 μ m.

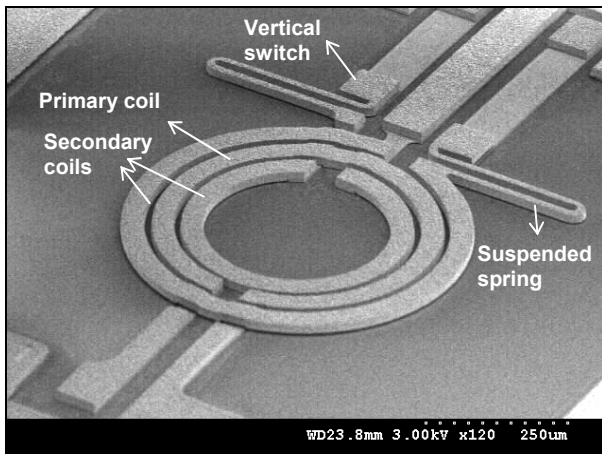


Figure 2. SEM view of a 20µm thick silver switched tunable inductor fabricated on Avatrel membrane.

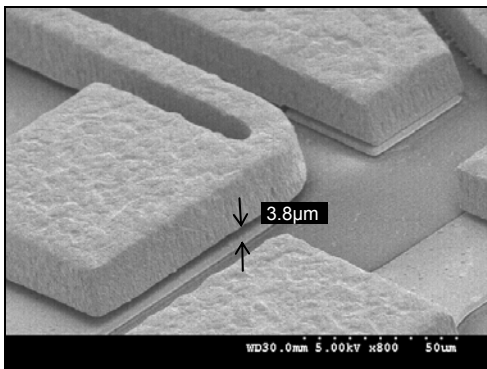


Figure 3. Close-up SEM view of the switch, showing the actuation gap.

FABRICATION

The packaged switched tunable inductor was fabricated using a post-CMOS-compatible process. The fabrication process flow is shown in Fig. 4 [6]. The substrate is first coated with a 20µm thick low-loss polymer (Avatrel). The routing layer is then formed by evaporating a thin layer of silver. The actuation gap is then defined by depositing 3.8µm thick PECVD sacrificial silicon dioxide layer. The coils and the switches are then formed by electroplating silver into a photoresist mold. Silver is used as the structural material since it has higher conductivity, lower young's modulus, and lower mechanical stress in electroplated film compared to other metals (*e.g.* copper). The loss of silicon (Si) substrate is eliminated by selective backside etching of Si underneath the device, leaving behind a polymer membrane. The device is then released in dilute HF. The micrograph of a fabricated un-packaged inductor taken from backside of the Avatrel membrane is shown in Fig. 5. The released device is wafer-level packaged in three simple steps [7]. First a thermally-decomposable sacrificial polymer (Unity) is applied and patterned. Then, the over-coat polymer, which has a higher decomposition temperature, is spin-coated and patterned. Finally, the sacrificial polymer is decomposed at 180°C.

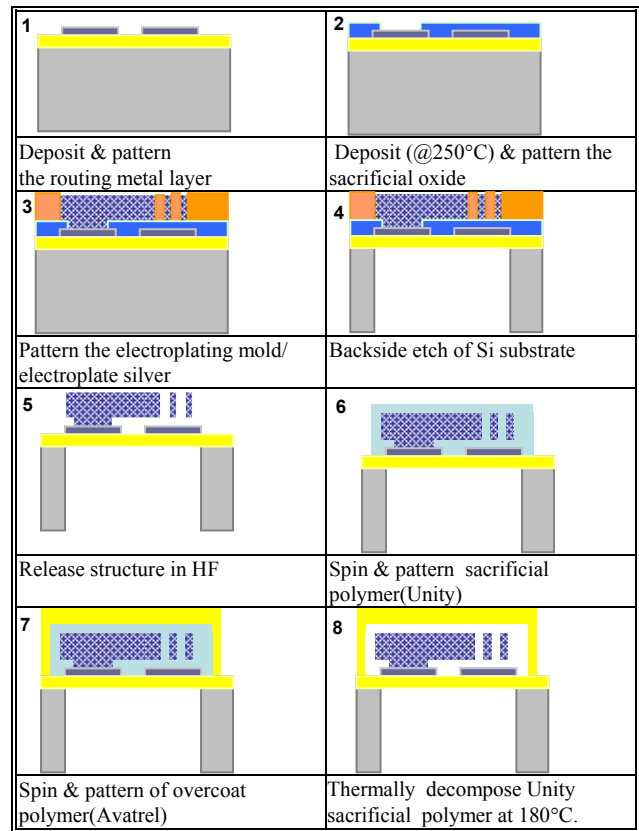


Figure 4. Packaged switched inductor fabrication process.

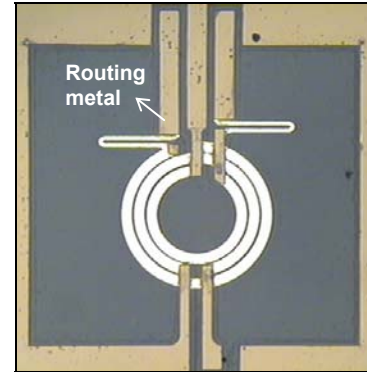


Figure 5. Micrograph of the switched Ag inductor taken from the backside of the Avatrel membrane.

DISCUSSION

Simulation and Test Results

The tunable inductors were simulated in Sonnet electromagnetic tool. Figure 6 shows the simulated effective inductance seen from port 1 at four states of the tunable inductor. As shown in Fig. 6, a maximum inductance change of 40% is expected when both switches are on. At higher frequencies, the magnetic coupling becomes stronger and the percentage change of inductance increases. The outer inductor is larger in size and introduces a stronger negative mutual inductance when switched on.

Several switched inductors were fabricated and tested. On-wafer S-parameter measurements were carried out using an *hp8510C* VNA and Cascade GSG microprobes. Figure 7 shows the measured inductance of a switched Ag inductor. The inductance was successfully switched to four different values and tuned from 1.01nH at 5GHz to 0.60nH when both coils are switched on, which represents a maximum tuning of 40% at 5GHz. The effective inductance drops to 0.78nH when the outer coil is on, and it becomes 0.82nH at 5GHz when the inner coil is on. The measured results are in good agreement with the simulated response as shown in Figures 6 and 7.

Measured and simulated *embedded Q* of this inductor in different states is shown in Fig. 8. As it is shown, the inductor exhibits a decent peak *Q* of 45 when the secondary coils are both off. The *Q* drops to ~25 when both switches are on. The drop of *Q* is consistent with (2). When any of the coils at port 2 are switched on, L_{eff} decreases while the effective resistance increases; consequently, the *Q* drops as the inductor is tuned.

Quality factor of the switched inductors can be improved by increasing the thickness of the routing layer. A fixed inductor with identical dimension to L_1 but with no routing layer exhibits a record high embedded *Q* of >120 at 5GHz, as shown in Fig. 9 [6]. SEM view of this inductor is shown in Fig. 10.

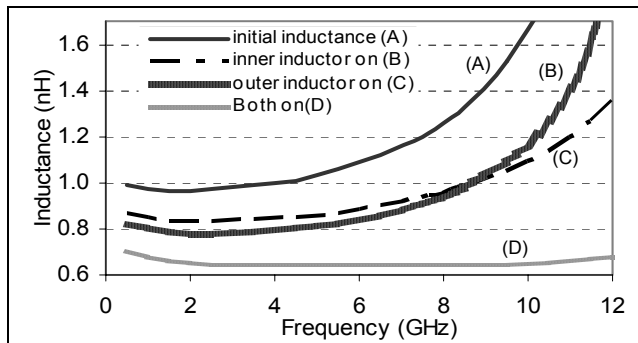


Figure 6. Simulated inductance showing a maximum tuning of 40% at 5GHz when both switches are on.

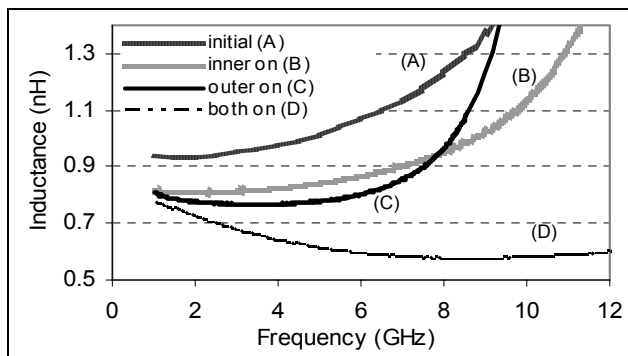
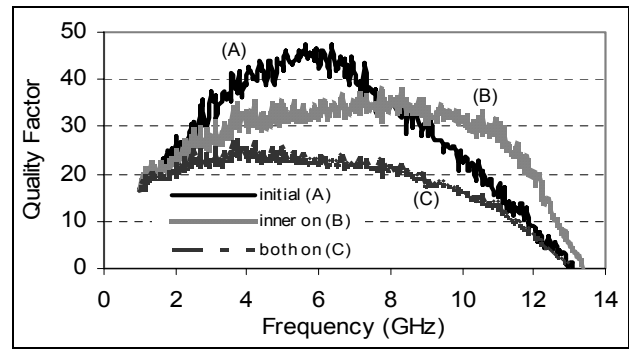
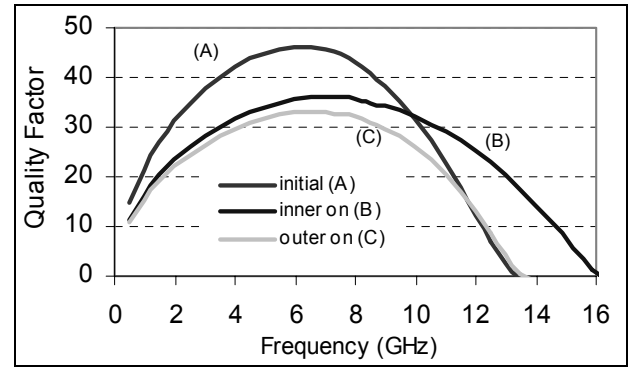


Figure 7. Measured inductance, showing a maximum tuning of 40% at 5GHz when both coils are on.



(a)



(b)

Figure 8. (a) Measured, and (b) simulated *embedded Q* showing the *Q* drops and SRF increases when the inner coil is on.

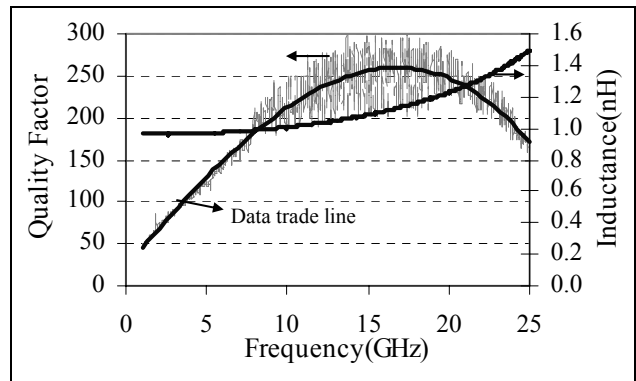


Figure 9. Measured *Q* and inductance of a one-turn 1nH inductor on Avatrel diaphragm, showing *Q* in excess of 120 at frequencies above 5GHz.

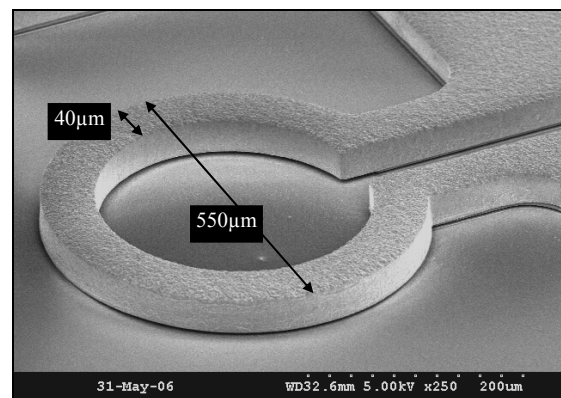


Figure 10. SEM view of the primary coil without routing layer, which exhibits $Q > 120 @ 5\text{GHz}$.

Packaging Test Results

Although silver has the highest conductivity of all metals, it has not been considered for RF integrated circuit applications because of its comparably fast electrical failure. A major problem that impedes the wide application of silver is the electrochemical migration of silver in the presence of moisture and applied bias. Silver migration usually occurs between adjacent conductors, which leads to the formation of dendrites that finally leads to an electrical short-circuit failure [8]. Hermetic sealing of silver microstructures increases the lifetime of the silver-made devices. In this work, we incorporated a semi-hermetic packaging technique to address silver failure issue and to encapsulate the tunable inductor. If necessary, subsequent over-molding can provide additional strength and resilience, and ensures long-term hermeticity.

Figure 11 is the SEM of the packaged switched tunable inductor and the close-up view of a broken package showing the air cavity inside. Figure 12 shows the Q of two identical inductors, one packaged and one un-packaged fabricated on passivated high-resistivity silicon substrate ($\rho > 1\text{K}\Omega\cdot\text{cm}$). As it is shown in Fig. 12, the switched tunable inductor showed no degradation in Q after packaging. The performance of the packaged inductor has not changed after 4 months.

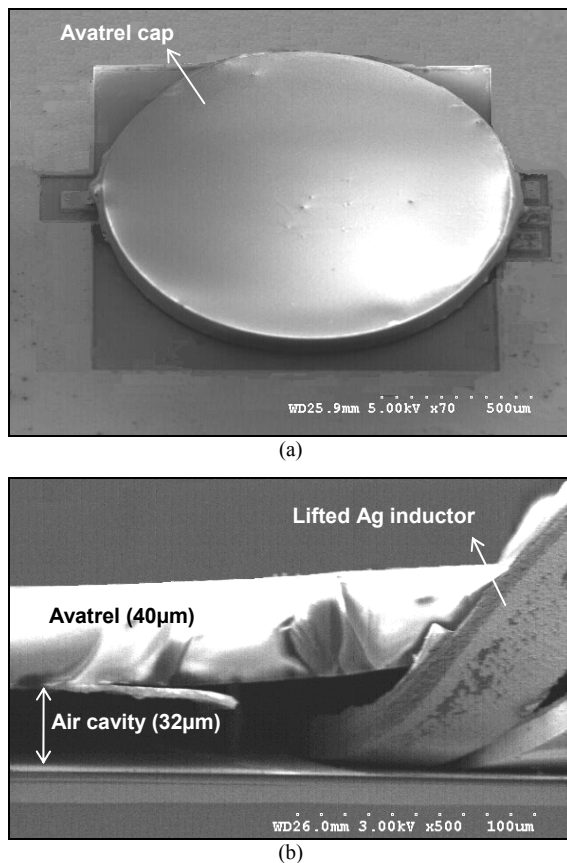


Figure 11. (a) SEM view of the packaged switched inductor and (b) the close-up view of a broken package showing the air cavity.

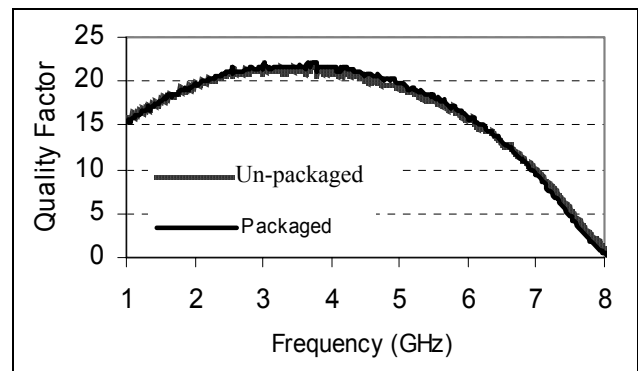


Figure 12. Measured embedded Q of two identical inductors when both switches are on, one packaged and one un-packaged.

CONCLUSION

A new implementation of high performance switched tunable silver inductors using a fully CMOS-compatible process was presented. A 1.01nH inductor was switched to four discrete values and showed a maximum tuning of 40% at 5GHz. Wafer-level polymer packaging of the tunable inductor did not cause any additional loss.

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