

A NEW INTEGRATION OF DEVICE-SCALE MICROPACKAGING WITH BI-DIRECTIONAL TUNABLE CAPACITORS

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ABSTRACT

This paper demonstrates a novel and device-scale vacuum-sealed variable capacitor that allows a movable capacitive plate to be actuated in bi-direction for large capacitance tuning. Meanwhile, the micro cap is served as the packaging structure as well as top electrode which can protect the variable capacitor structure from undesired physical attack. By taking advantages of device-scale micro cap, the subsequent packaging procedures are able to utilize conventional I.C. packaging, minimizing changes due to an addition of integrated MEMS devices. Furthermore, the vacuum sealing can also be achieved to reduce phase noise and to alleviate the thermal, humid, and air damping effect. This approach is compatible with CMOS process and able to integrate micromachined variable capacitor and electric circuit into a single chip.

INTRODUCTION

In modern wireless systems, high-quality voltage-controlled oscillators (VCOs) that contain variable capacitors demand wide tuning range and low phase noise in the several gigahertz frequency ranges. However, the quality factor of the conventional varactors is relatively low at high frequency and it exhibits a high phase noise VCO. Fortunately, with the advance of the MEMS technology, the variable capacitors with high-Q factor and wide tuning range up to 100% have thus far been reported [1,2]. Nevertheless, the thermal vibration of these MEMS variable capacitors contributes an additional phase noise [3]. It was found that the best way to resolve this issue is to operate these MEMS variable capacitors in the vacuum environment. However, the scheme to package these movable devices as well as integrated circuits co-existed on a chip surely requires additional, specific processes as well as associated cost. As a result, a suitable packaging approach with ease of fabrication, conventional I.C. packaging compatibility, and low cost is desperately needed.

In this paper we present an approach that is able to miniaturize a packaged tunable capacitor capable of co-existing with integrated circuits onto a single chip, as shown in Fig. 1. The micropackaging may also achieve a vacuum sealing that alleviates thermal,

humid, and air damping adverse effect as well as phase noise. Furthermore, the subsequent packaging procedure may utilize existing I.C. packaging process that minimizes a change of existing solutions, thus potentially reducing additional equipment investment.

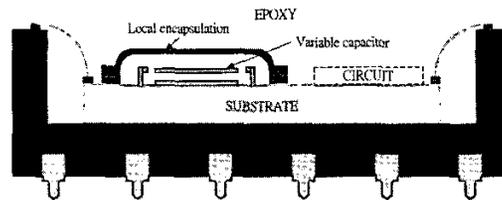


Fig. 1 The concept of device-sealed micropackaging

DESIGN

(A) Device configuration

Due to the nature of the electrical device, the maximum tuning range of a parallel plate capacitor reaches 50%. In the design of this work to enlarge the tuning capacity, the bi-directional tunable capacitor that consists of both fixed electrodes and a sandwiched movable nickel plate is presented, as shown in Fig. 2. Its cap structure not only provides device protection, but also serves as a fixed electrode. In a bi-directional tunable capacitor, the movable plate can either be attracted downward the bottom electrode or upward the top electrostatically, leading to a large tuning range of capacitance.

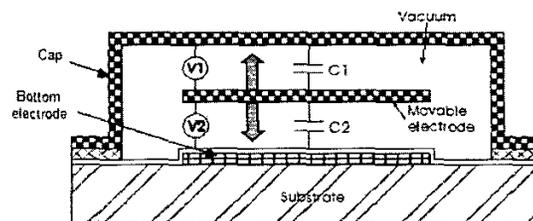


Fig. 2 A schematic view of the bi-directional actuated variable capacitor

(B) Fabrication Consideration

The parallel plates can be easily accomplished by surface micromachining, and its associated gap can also be precisely determined. However, in a vacuum sealing enclosure, high stiffness of a cap structure is required to sustain an ambient pressure of

around 1 atm without deformation. A regular thin film of surface-micromachined polysilicon poses a serious challenge to achieve such requirement. Electroplated nickel is then chosen to take into consideration for its superiority in mechanical property, electrical conductance, process compatibility and thickness variation. To achieve such a stringent requirement, a flip-chip solder-bonded assembly is newly developed. The new approach employs an assembly-transfer technique that the cap structure is fabricated on a different substrate, then transferred onto the device substrate as illustrated in Fig. 3.

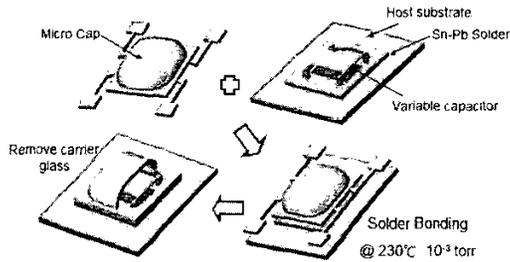


Fig. 3 An assembly transfer technique for a device-scale bi-directional variable capacitor.

(C) Analysis

(1) Cap Membrane Deflection

In a vacuum sealing, the cap structure exerted by externally ambient pressure of around 1 atm may result in a membrane central deflection as shown in Fig. 4. Therefore, an analysis is also needed to obtain a required structural thickness in a vacuum enclosure, which is sustainable in an ambient pressure. In ANSYS numerical simulation and mathematical analysis, the results show that when the nickel cap is 15 μm or above, the central deflection of the cap in an ambient atmosphere is less than 3 μm in our design.

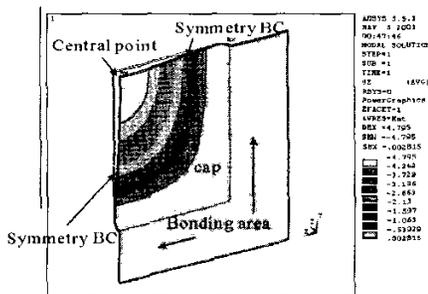


Fig. 4 Simulation of a vacuum sealed cap deformed in an ambient atmosphere

(2) Mechanical Properties of Variable Capacitors

It is also noted that the mechanical resonant

frequencies of the variable capacitor must be far lower than its signal frequency to prevent from the capacitor vibration interference with the signal frequency as well as a lower phase noise. Fortunately, the mechanical resonant frequencies of the variable capacitor are always lower than the signal frequency for the applications of the wireless communication.

In order to lower the driving voltage of the variable capacitor, the folded beams shown in Fig. 5 are designed. Also, the variable capacitors are made in metal material to improve the electric quality factor.

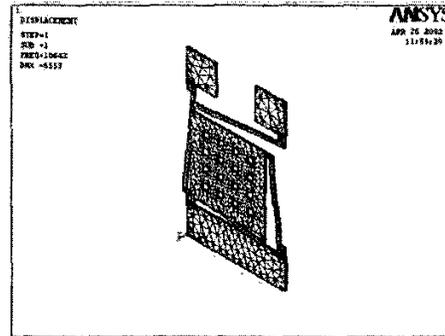


Fig. 5 Mechanical structure design for the variable capacitor

FABRICATION

The process flow of this packaged capacitor using micro assembly transfer technique is illustrated in Fig. 6. This packaged capacitor consists of two parallel plates and a micro cap. The parallel plates can be accomplished easily by surface micromachining, and the micro cap is fulfilled using flip-chip solder-bonded assembly that is transferred from a glass carrier. The capping structure is first made from etched pits on the carrier glass wafer. Aluminum is then deposited and serves as a sacrificial layer. The capping structure is then formed while electroplated, subsequently electroplated with solder bumps. In an appropriate design of patterns that most sacrificial layer of aluminum is removed, the resultant nickel cap is freed, suspended through long tethers attached on the carrier glass. The critical alignment of flip chip assembly to the host substrate is alleviated, which avoids vast capital investment of high precision equipments. The cap structure on a carrier is then flipped, aligned through the glass, and bonded in soldering to a host substrate. External pulling is applied to remove the carrier glass, leaving the micro cap on the host substrate, and the packaged variable

capacitor is accomplished. First, the micro cap and variable capacitor are fabricated on carrier glass and host substrate respectively. The micro cap is then aligned through the transparent carrier glass and bonded to host substrate at 230 °C in a pressure of 10^{-3} torr. After the bonding is completed, the carrier glass is pulled up to break down tethers, thus leaving the micro cap staying on the host substrate.

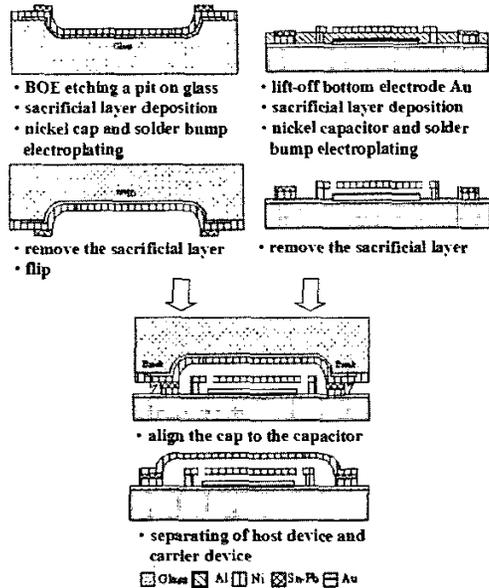


Fig. 6 Fabrication and micropackaging process flow

RESULTS AND DISCUSSION

Fig. 7(a) shows a complete micro cap, which is formed around 18 μm in thickness and 40 μm in housing height and the encapsulation covers an area of 2200 μm x 1500 μm , which is sufficiently large to encapsulate most sizes of micro devices. The solder reflow technique of the bonding mechanism is chosen to be an approach for a hermetic sealing. Additionally, the melted solder was emerged over through holes on the peripheral fringe of the cap, which in turn firmly adhered the cap to the substrate. Fig. 7(b) describes the electrostatically driven variable capacitor with a ring of SnPb solder bump around it. The suspended beams are designed to lower the driving voltage and the etching holes are used to release the sacrificial layer.

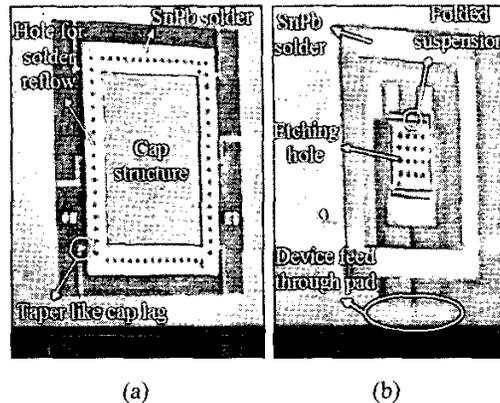


Fig. 7 (a) Fabricated microcap suspended on a glass carrier (b) The variable capacitor made on a host substrate

After the flip-chip assembly technology was used, a transferred micropackaged bi-directional tunable capacitor was accomplished as shown in Fig. 8. The electrical feed-through device pads can also be seen outside of the encapsulation.

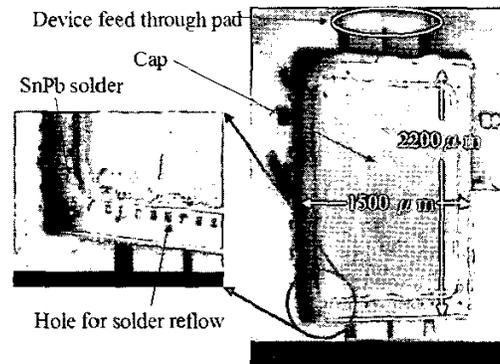


Fig. 8 Complete encapsulation of a capacitor

In Fig. 9, the mechanical quality factor of the actuated capacitor was measured with the impedance analyzer to be 10 times larger than that in an ambient testing. The result shows a significantly high quality factor in a reduced air-damping effect. The paper ensures that the vacuum sealing was achieved in such a device-scale encapsulation.

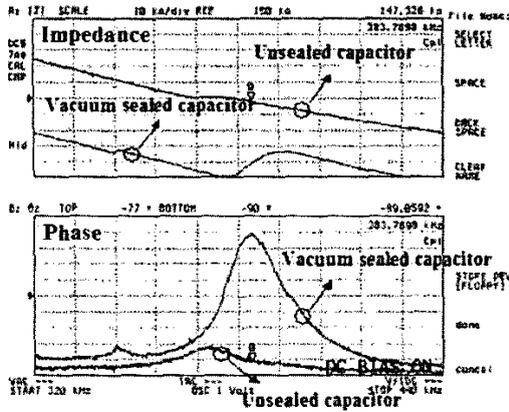


Fig. 9 The structure resonance of vacuum-sealed and unsealed capacitor

Fig. 10 shows the relation between the tuning capacitance and applied voltage in which the positive and negative voltages account for required actuation of the movable capacitive plate downward and upward to the fixed electrodes, respectively. It was found that the present capacitor can be tuned in a range of 56.5% of capacitance.

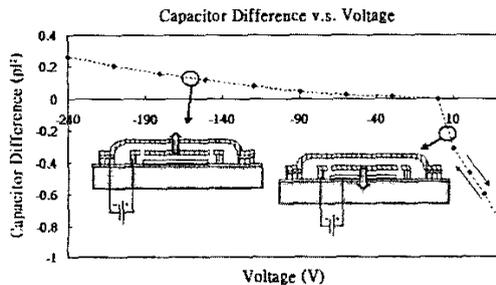


Fig. 10 The static relation of the bi-directional variable capacitor vs. voltage

In Fig. 11, the performance of the variable capacitor at high frequency was measured by network analyzer, Agilent 8722ES. As the mechanical resonant frequency of the movable capacitor plate was found in 5.4 GHz, its associated series resistor was measured to be 30Ω . The series resistor appears relatively high, adverse to signal transmission. To exclude the effect of the variable capacitor, an open transmission line was conducted. The series resistor was found to be 20Ω in the open transmission line due mainly to the thin bottom electrode and high nickel resistive property.

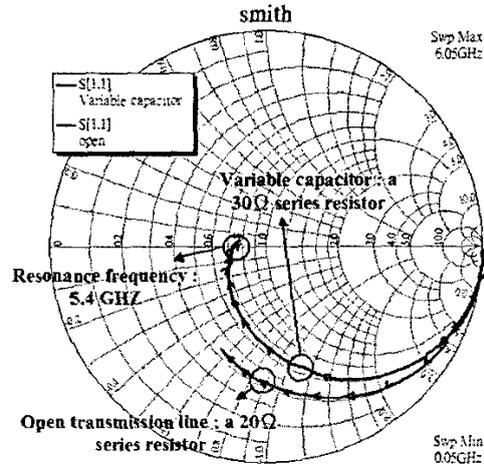


Fig. 11 The measured high-frequency performance of the micropackaged tunable capacitor

SUMMARY

This paper demonstrates a successful integration of device-scale vacuum micropackaging with a functional tunable capacitor. The bi-directional actuation allows the capacitor in a large capacitance tuning range of 56.5%, potentially up to 100%. The packaging scheme provides a solution of packaging miniaturization, potential co-existence of integrated circuits, and existing packaging compatibility.

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