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Microelectromechanical capacitor with wide tuning range

H. Nieminen, V. Ermolov and T. Ryhänen

A new anchoring design is proposed for a microelectromechanical (MEM) capacitor that allows realisation of wide tuning range devices. The MEM capacitor is made of gold using surface micromachining. The capacitor has a capacitance of 1.58 pF and achieves a tuning range of 2.25:1 with parasitics.

Introduction: Voltage controlled capacitors are key elements in many microwave and millimetre wave applications, for example tunable matching networks, voltage controlled filters, and voltage controlled oscillators (VCOs) [1, 2]. The variable capacitors that are required in these applications can be implemented with *pn*-junctions [3]. However, since these applications require a high quality factor (Q) and a wide tuning range [2], it has been proposed that metallic surface micromachined microelectromechanical (MEM) capacitors could be used [4, 5]. The main advantages of the MEM capacitor are the low series resistance when metal is used as a structural material, the ability to keep the signal circuit apart from the control circuit, and mechanical inertia that isolates the mechanical dynamics from the radio frequency electrical signals.

MEM capacitor: A voltage controlled MEM capacitor usually consists of two electrodes. One is fixed to the substrate and the other suspended over the fixed electrode using mechanical springs. When the bias voltage is applied between the electrodes, electrostatic force attracts the suspended electrode towards the fixed electrode. The bias voltage attracts the suspended electrode towards the bottom electrode until equilibrium between the mechanical spring force and the electrical force is reached. Since the spring force is a linear function of the gap and the electric force is inversely proportional to the second power of the gap, there is a stable equilibrium point only when the air-gap is more than 2/3 of the original air-gap. Therefore, the theoretical maximum capacitance tuning range of the one-gap structure is limited to 50%. However, the tuning range can be increased using a two-gap structure with separate control and signal electrodes [5]. Fig. 1 shows the operational principle of a one-gap and a two-gap MEM capacitor. If, in the two-gap structure, the gap between the control electrode and the suspended electrode is three times larger than the gap between signal electrode and the suspended electrode, the control voltage pull-in does not limit the maximum tuning range.

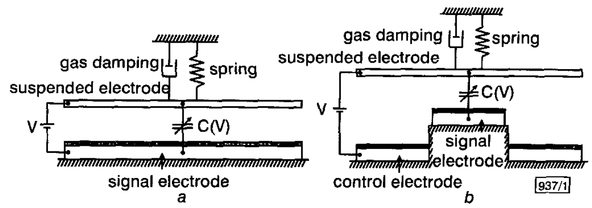

Fig. 1 *Functional models of one-gap and two-gap MEM capacitors*

a One-gap MEM capacitor
b Two-gap MEM capacitor

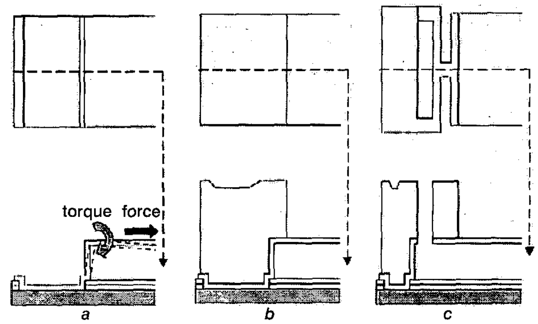

Fig. 2 *Torque on suspended membrane owing to stress induced force, proposed firm anchoring structure using thick electroplating and advanced anchoring structure using thick electroplating to form springs having low series resistance*

a Torque on membrane
b Proposed anchoring structure
c Advanced anchoring structure

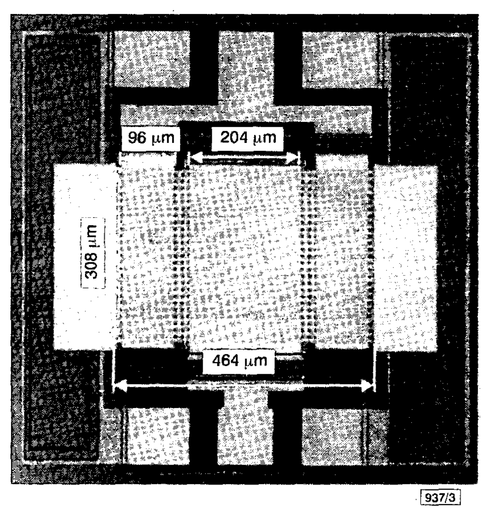

Fig. 3 *Photograph of two-gap tunable MEM capacitor with firm anchoring*

Nominal air-gaps of signal and control electrodes are 0.5 and 1.5 μm, respectively

The problem with the MEM capacitor is that to achieve capacitance values suitable for the above-mentioned applications [1, 2] within reasonable device area, the air gap has to be controlled accurately. Typically the required air gap is in the range of 0.3–2 μm while the width and length of the suspended electrode are ~100–500 μm. The accuracy of the air gap is mainly dependent on the planarity of the suspended electrode and the stability of the anchoring. The suspended metal electrode often has intrinsic stress and thermal stress due to the mismatch of thermal expansion coefficients of the substrate and the metal film. It can be shown using finite element modelling that these stresses create forces that act on the anchoring points. Fig. 2*a* shows how these forces may cause torque on the suspended electrode at the anchoring point. Even a small torque due to improper anchoring design can cause severe warping of the suspended electrode. Fig. 2*b* shows the proposed firm anchoring design that minimises torque on the suspended electrode. The anchoring is enforced using a thick electroplated metal. The same thick electroplated metal can be used to create high Q inductors, on the same chip. Fig. 2*c* shows a more advanced anchoring structure that uses the thick electroplating also to form springs that have low series resistance while lowering the stresses on the suspended membrane.

Fig. 3 shows a capacitor with firm anchoring (Fig. 2*b*) that was fabricated by Tronic's Microsystems, France. The structural material of the capacitor is gold and the substrate is low resistivity silicon. In order to reduce the parasitic capacitance, the substrate was removed under the signal electrode using anisotropic dry etching.

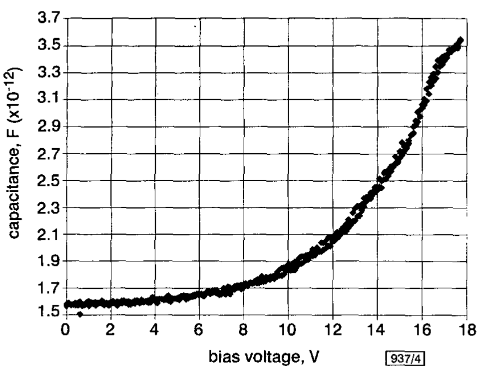

Fig. 4 *Measured capacitance against voltage behaviour of two-gap MEM capacitor*

Control voltage stepped from 0 to 17.7 V and then back to 0 V. Substrate was not removed under signal electrode of device

Results and discussion: All measurements were carried out at room temperature using a Karl Suss PA 200-II probe station that has temperature control and a dry air flow system. Low frequency capacitance against voltage was measured using an HP 4284A LCR meter and an HP 6634B DC voltage source. The pad parasitics were not reduced from the low frequency measurements. S-parameters were measured using a Rohde&Schwarz ZVCE vector network analyser. Open and short structures that are located besides every device were used to remove pad parasitics from the S-parameter measurement results.

Fig. 4 shows the measured capacitance against control voltage of the MEM capacitor. The capacitor has a measured tuning range of 125%. When the control voltage is stepped from 0 to 17.7 V and then back to 0 V, the capacitance changes from 1.58 up to 3.55 pF. The substrate was not removed under the devices used for the capacitance measurements. Consequently, future studies with reduced parasitic capacitance will improve the capacitance tuning range considerably. There is a slight hysteresis visible in the capacitance behaviour. It seems that the AC probe signal of the LCR meter causes the hysteresis. The AC signal is rectified owing to a square law relation between the electrostatic force and the signal voltage. This causes an additional voltage component between the signal electrode and the suspended electrode. If the suspended electrode touches at some points of the signal electrode, slight hysteresis results. The high frequency measurement yields a total capacitance of 1.44 pF and a Q of 53 that were calculated from S_{11} data at 2 GHz. The substrate was removed under the signal electrode of this device.

Conclusion: Using the proposed anchoring structure a large tuning range MEM capacitor that is feasible for many applications [1, 2] has been realised. The measured Q is limited mainly by substrate losses. Simulations indicate that a major improvement in the Q can be achieved by replacing the low resistivity silicon substrate with a non-conducting material like glass. However, a drawback of the two-gap capacitor is the need for large tuning voltage. In addition, the temperature stability of the fabricated devices depends on the intrinsic stress of the metal films. The analysis of the temperature dependence and long-term stability are the key focuses of the on-going research.

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Low-loss 1.5%-Δ arrayed waveguide grating with narrow laterally tapered spotsize converter

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A low coupling loss of 0.5 dB/point between 1.5%-Δ silica-based waveguides and a singlemode fibre has been achieved by employing a simple laterally tapered waveguide with a narrow core width. By applying this structure to an arrayed waveguide grating multiplexer, the insertion was decreased loss from 4.9 to 2.6 dB.

Introduction: The silica-based planar-lightwave-circuit (PLC) is a low-loss, highly-reliable, and cost-effective optical device, which has become a key component in optical communication systems. Recently, the bending radius of PLCs has been reduced by increasing their relative refractive index difference (Δ) to enable optical circuits to be integrated more densely [1]. This characteristic allowed the fabrication of a 400 channel arrayed waveguide grating (AWG) multiplexer on a super-high-Δ (SHΔ) waveguide [2]. However, as Δ is increased, a mode field pattern mismatch occurs between an optical fibre and a PLC. This leads to an increase in the coupling loss, which is a significant problem limiting the advantages of an SHΔ PLC.

Various optical waveguide spotsize converters have been studied to compensate for this increased coupling loss. Of the numerous spotsize converters that have been proposed, the laterally tapered waveguide is the simplest and most cost-effective structure since it does not require any additional fabrication processes. Low-loss coupling between a semiconductor device and a singlemode fibre has been reported with this simple structure [3]. However, since