RF MICROMACHINED VARACTORS WITH WIDE TUNING RANGE

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ABSTRACT

Polysilicon surface micromachined varactors using two- and three-plate structures with 1.5:1 and 1.87:1 tuning ranges, respectively, are presented. The tuning ranges are near-theoretical limits and can be obtained within 4.4 V control voltage. The two-plate varactor has a nominal capacitance of 2.05 pF and a Q-factor of 20 at 1 GHz.

1. INTRODUCTION

High quality tunable passive components such as varactors are essential elements in RF voltage-controlled oscillators (VCOs) and tunable filters. A low-noise VCO needs high Q-factor components since its phase noise is proportional to $1/Q_T^2$ where Q_T is the overall Q-factor of the LC tank [1]. Additionally, a highly linear LC tank is needed for RF filter applications [2].

Recently, micromachined varactors have been shown to have an adequate Q-factor when they are fabricated in either an aluminum [3] or a polysilicon [4] surface micromachining technology. These varactors are expected to offer an excellent linearity since they do not respond to high frequencies outside their mechanical resonance frequencies. However, their tuning ranges thus far have been less than the theoretical limits [3]-[4].

This paper reports two- and three-plate polysilicon micromachined varactors that have the largest tuning range reported to date.

2. VARACTOR DESIGN

Two- and three-plate varactors have been designed and fabricated in a polysilicon surface micromachining process (MUMPS) which features three layers of polysilicon and one layer of gold [5]. Despite the superior electrical properties of aluminum, polysilicon was chosen as the structural material for varactors due to its good mechanical properties [6].

A two-plate micromachined varactor consists of a fixed plate and a suspended plate (Fig. 1). A dc voltage V_1 applied across the plates causes an electrostatic force which moves the suspended plate closer to the fixed plate, and thus increases the desired capacitance C_D. It can be shown that the maximum theoretical tuning range of such varactor is 1.5:1 [3].

A prototype two-plate varactor was designed with a nominal capacitance of 0.57 pF and a maximum capacitance of 0.85 pF when $V_1 = 3.3$ V. To minimize the varactor loss, the most conductive layers (Poly1 and Poly2/Gold layers) were chosen for the varactor plates. Given 0.75 μm spacing between Poly1 and Poly2, the size of the varactor plates must be 210 μm by 230 μm. To achieve the desired tuning range, a suspension with a spring constant of 37.2 N/m is needed. The mass of the suspended plate, which is composed of the top Poly and Gold layers, is 0.6 μg, and the mechanical resonant frequency is estimated to be 39 kHz. A fixed parasitic capacitance of approximately 0.37 pF appears in parallel with the variable capacitor.

A three-plate micromachined varactor consists of a suspended plate and two fixed plates (Fig. 2). The top and bottom plates are mechanically secured while the middle plate is suspended by some spring arrangement. Since dc voltages V_1 and V_2 can now be used to either increase or reduce the desired capacitance C_D, a wider tuning range can be achieved. It can be shown that the maximum theoretical tuning range of such varactor is 2:1 if distances between the plates are the same [4].

An experimental three-plate varactor was designed with a nominal value of 1.9 pF. A spring constant of 122 N/m is needed to accommodate the maximum capacitance of 2.85 pF when $V_1 = 3.3$ V and $V_2 = 0$ V. To obtain the required nominal capacitance, a 400 μm by 400 μm capacitor plates are used. The mass of the suspended plate, which consists of Poly2 layer, is then 0.7 μg and the mechanical resonant frequency is estimated to be 66.5 kHz. The fixed parasitic capacitance that appears in parallel with the varactor is estimated at approximately 0.6 pF. Dimples are used to prevent the middle plate from sticking to the bottom plate in the presence of excessive bias voltage V_2.

The standard pad in the MUMPS process has a parasitic capacitance of 1.5 pF which limits tuning range. To minimize parasitic capacitance of the pad, a low parasitic pad has been developed that has a parasitic capacitance of 0.25 pF. A smaller capacitance per area is achieved by the use of only Poly2 and Gold layers, which are deposited on 2.25 μm thick oxide prior to sacrificial layer release. To protect the oxide underneath the pad from HF etch, anchors are placed around the edges of the pad. In addition, a smaller 86 μm by 86 μm pad is used.

3. RESULTS AND DISCUSSION

All measurements were done using an HP 8753D network analyzer, a Cascade probe station, and WinCal software. The measurements include the parasitic capacitance of the pads.

The microphotographs of the two- and three-plate varactors are shown in Fig. 3 and Fig. 4, respectively. An HF etch followed by a CO_2 drying process were used to release the experimental devices [5]. The holes in the plates are required in order to ensure the proper HF etch of the sacrificial layers.

The prototype two-plate micromachined varactor has a measured nominal capacitance of 2.05 pF when $V_1 = 0$ V and a Q-factor of 20 at 1 GHz (Fig. 5). The varactor is tunable from 2.05 pF to 3.09 pF as the bias voltage V_1 is swept from 0 V to 4 V, and the tuning range is 1.5:1 (Fig. 6). Statistics show that the average measured nominal capacitance is 1.98 pF and the standard deviation is 0.14 pF using the data from 14 functional devices (16 devices were fabricated).

The experimental three-plate device has a measured nominal capacitance of 4 pF when $V_1 = 0$ V and $V_2 = 0$ V and a Q-factor of 15.4 at 1 GHz (Fig. 7). The capacitance is tunable from 3.4 pF ($V_1 = 0$ V and $V_2 = 4.4$ V) to 6.35 pF ($V_1 = 1.8$ V and $V_2 = 0$ V), and the tuning range is 1.87:1 (Fig. 8). Out of the 96 fabricated devices, 7 varactors were not functional. The average measured nominal capacitance was 3.63 pF and the standard deviation was 0.52 pF.

A 100 Hz, 3 V square-wave was applied accross the two-plate varactor in order to test the reliability of a micromachined varactor. No change in varactor characteristics has been observed even after 60 milion cycles.

Experimental devices exhibit some degree of plate buckling, which manifests itself in a higher measured nominal capacitance than the designed value. Furthermore, in a case of the three-plate varactor, buckling of the suspended plate is suspected to be responsible for bistability of the three-plate varactor which limits the minimum capacitance value that the varactor can be tuned to without a discontinuity. Structures with low residual stress are being investigated to minimize this effect so that the tuning range of three-plate varactors can be further improved.

The Q-factor of micromachined varactors is limited by the series resistance of the interconnect. Alternative suspension designs that can provide the desired spring constant and have a low series resistance will be also investigated. In addition, future designs will use wider interconnect in order to increase the Q-factor even further.

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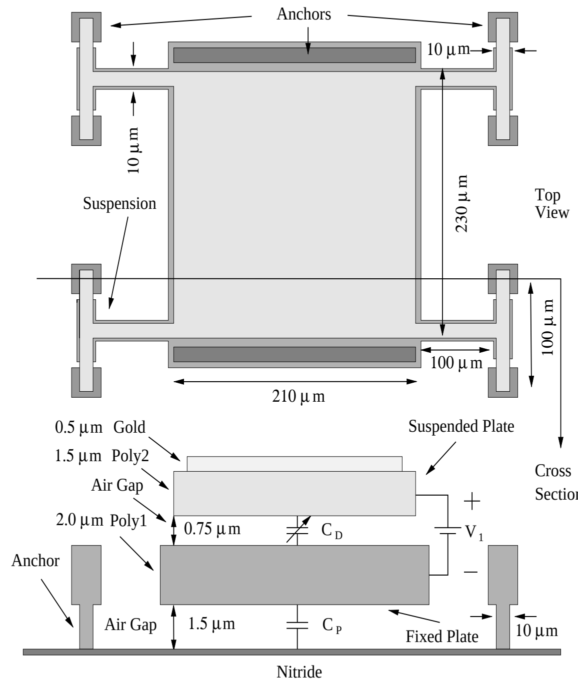

Fig. 1. Top and cross-section views of the two-plate micromachined varactor.

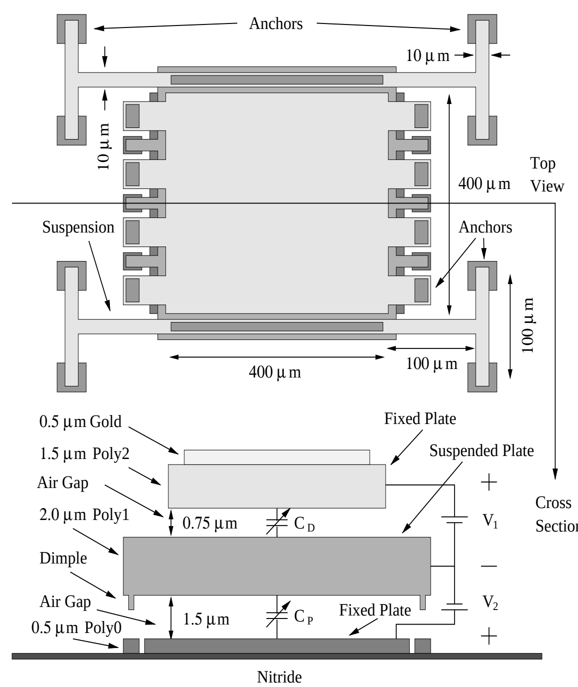

Fig. 2. Top and cross-section views of the three-plate micromachined varactor.

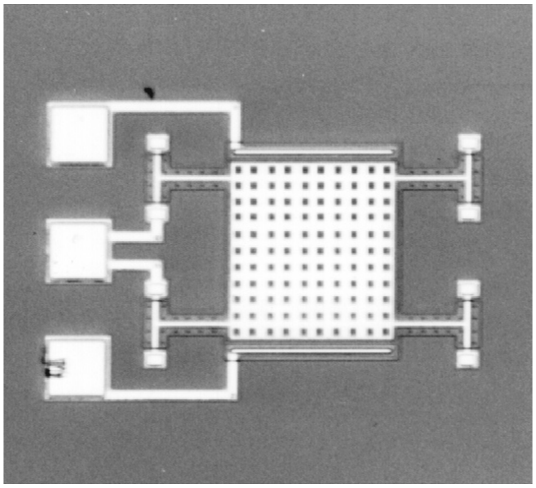

Fig. 3. Microphotograph of the two-plate varactor.

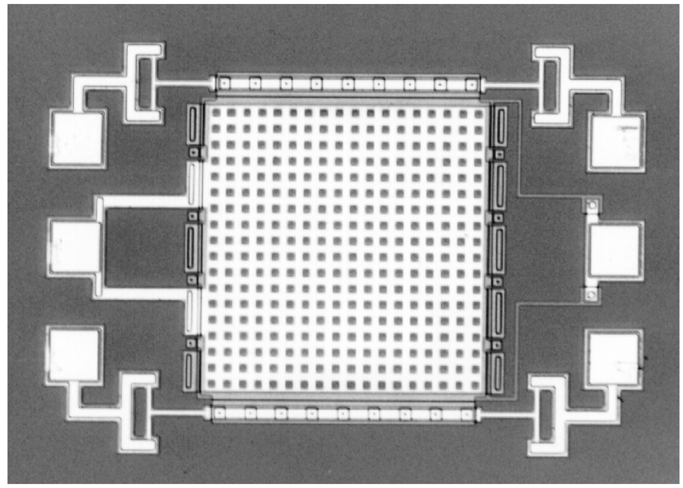

Fig. 4. Microphotograph of the three-plate varactor.

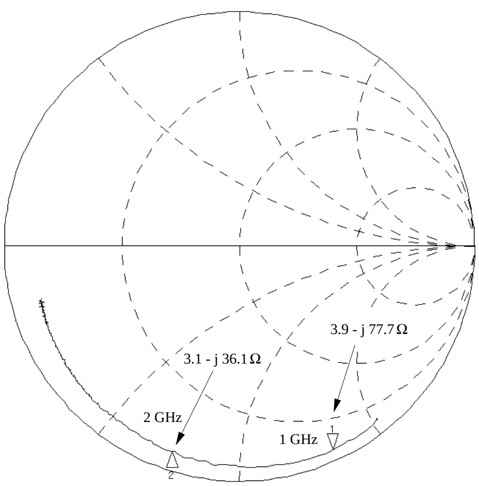

Fig. 5. Measured S_{11} of the two-plate varactor ($V_1 = 0$ V).

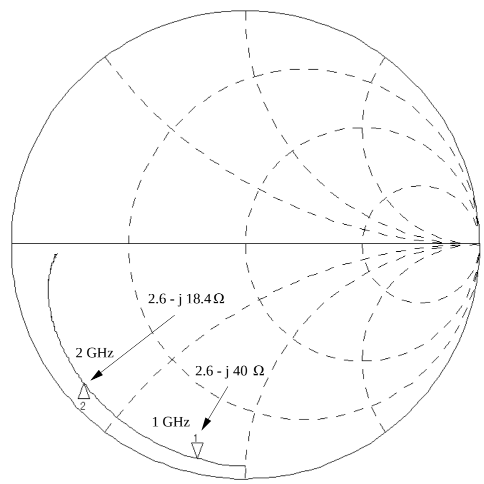

Fig. 7. Measured S_{11} of the three-plate varactor ($V_1 = 0$ V & $V_2 = 0$ V).

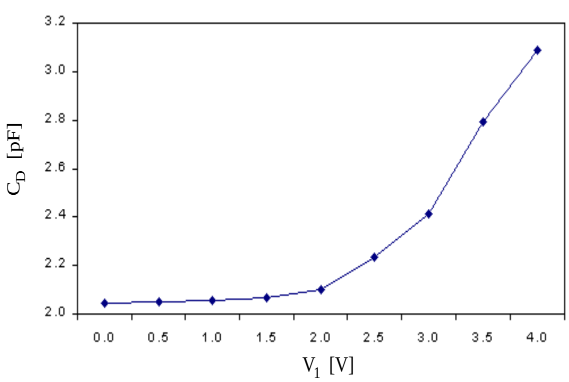

Fig. 6. Tuning characteristics of the two-plate varactor.

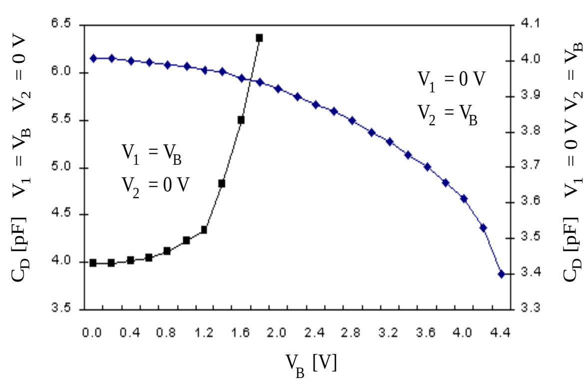

Fig. 8. Tuning characteristics of the three-plate varactor