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MEMS varactors: challenges for large tuning ratios

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Summary:

Different modern applications, such as tuner circuits, high-frequency voltage-controlled oscillators (VCO), RF-filters, radio front-end systems as well as many sensor systems require adjustable electrical capacitances – called varactors. The standard semiconductor varactors are strongly limited in the maximum reachable tuning ratio (TR), which is needed to cover bigger frequency ranges. This paper presents a possibility use of micro electro-mechanical (MEMS) varactors instead, to achieve high TR, analyze the challenges from different aspects and propose an example design of it.

Keywords: MEMS, Varactor, RF-systems, Tuning ratio, NED

Introduction

In recent years, RF Microelectromechanical Systems (RF-MEMS) have gained significance due to advancements in telecommunications, IoT, and Industry 4.0. These RF-MEMS systems find applications in various areas such as tunable antennas, parametric amplifiers, phase shifters, tunable filters and in general RF frontends [1]. Today applications are mostly based on the semiconductor RF-varactors, which have some limitations like a small tuning ratio. To cover larger frequency spectrums or tuning ranges, many different separate semiconductor varactors could be utilized, complicating the system and increasing its footprint.

Advancements in MEMS fabrication technology enable the creation of RF-MEMS varactors with higher tuning ratios and provide a potential replacement for multiple semiconductor varactors. In addition, RF-MEMS, have lower losses, minimal power consumption and negligible phase noise, making them suitable for autonomous front-end systems [2].

The mechanical variation of electrical capacitance in MEMS-varactors is typically achieved by changing of the gap g between the electrodes or by changing the overlapping area A of them, what could be seen from the basic formulae of the plate capacitor:

$$C(A,g) = \frac{\varepsilon_0 \varepsilon_r A}{g} \tag{1}$$

The tuning ratio TR is defined as a simple ratio of the maximum capacitance to its minimum value.

$$TR = \frac{C(A,g)_{max}}{C(A,g)_{min}} \tag{2}$$

To maximize the achievable tuning ratio, several challenges must be overcome. In the following, different challenges and aspects are discussed as well as possible solutions are presented.

Choice of Actuation and Working Principle

The most common actuation principle in the typical MEMS-applications is based on electrostatic attraction between the electrodes. It is fast, robust and energy efficient. One of the disadvantages of classical electrostatic drives is the pull-in problematic. It is caused by the squared change in the electrostatic force (3), whereas the restoring force (4) remains linear with the narrowing gap of x.

$$F_{el} = \frac{1}{2} \frac{\varepsilon_0 \varepsilon_r A}{(g_0 - x)^2} V^2 \tag{3}$$

$$F_s = -kx \tag{4}$$

The static pull-in point, at which both forces can just barely compensate each other, can be calculated from the equilibrium state and results in $g_0/3$ [3]. Hence, just one third of the initial gap can be used as a stroke, after that both electrodes rapidly stick together.

Since the electrostatic force is proportional to the square of the applied voltage (3), any

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mechanical deflection, or movement respectively, is due to the linear spring constants a function of V^2 as well. This also applies to both principles of capacitance variation here: altering the gap distance $g(x) = (g_0 - x)$ or changing the overlap area $A(y) = y \cdot l$.

To optimize the tuning ratio the capacitance variation per voltage unit should be maximized.

$$\frac{dC}{dV} = \frac{\varepsilon_0 \varepsilon_r l}{g_0} \cdot \frac{dy}{dV} \quad (5)$$

$$\frac{dC}{dV} = -\frac{\varepsilon_0 \varepsilon_r A}{(g_0 - x)^2} \cdot \frac{dx}{dV} \quad (6)$$

In case of the area variation (5), the capacitance change is always linear regarding to the plate movement y. But in the case of gap variation (6), the capacitance behaves hyperbolically with gap narrowing x. The closer both electrodes are, the higher varies the capacitance. Therefore, it is recommended to use this region to maximize the tuning ratio. The dilemma here is that the electrostatic force (3) becomes very high at narrow distances and for compensation a high spring force is required. Otherwise, the electrodes collapse due to the pull-in instability. But a high spring force, on the other side, generates a stiffer mechanical structure, which one resists more any further deflection. To alleviate the problem, it is possible to use an additional compensating electric field that moves electrodes that initially are close together further apart. That allows to make the movable electrode less stiff and to use the region of high capacitance change simultaneously, see Fig. 1.

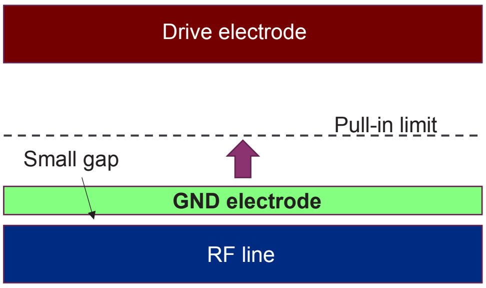

Fig. 1 Schematical cross-section of a bridge-varactor for a high capacitance variation

In this configuration the maximum capacitance would be in non-actuated state and the capacitance is tuned down proportionally to the driving voltage.

Reduction of Parasitic Capacitances

One of the biggest challenges to achieve higher tuning ratios of varactors is the presents of unavoidable parasitic static capacitances C_{par} in the system. Due to their parallel connection, they always express themselves in addition to the varactor capacity. They are static and limit the ratio by:

$$TR = \frac{C_{max} + C_{par}}{C_{min} + C_{par}} < \frac{C_{max}}{C_{min}}, \quad (7)$$

all the more so as the maximization of the ratio should often be realized by minimizing C_{min}. Such parasitics are created by fix structures in the periphery, like routing of the circuit paths as well as in the varactor construction itself. Thus, the conducting paths in the circuit periphery should be as short and separated as far as possible and their dielectric isolation material should have a rather low permittivity ϵ_r.

The varactor mechanics consists of moving and non- or less moving parts. The latter can also cause a kind of parasitic capacitance. Fig. 2a shows the bending of a GND electrode clamped on both sides. There is almost no movement in the vicinity of the clamps and a rather static capacitance is created, which can lower the TR. In order to minimize this undesirable effect, the width of the RF line can be reduced as shown in Fig. 2b.

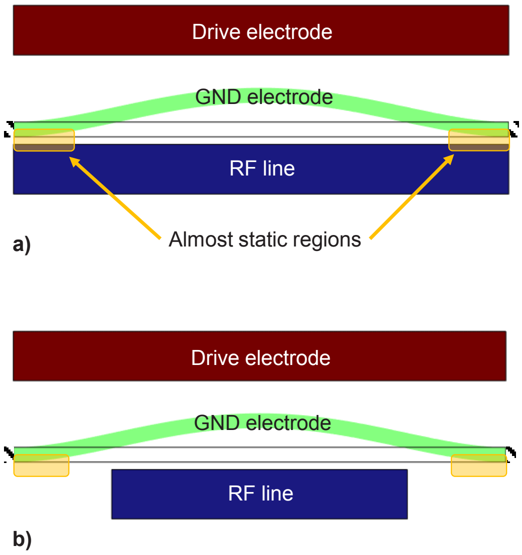

Fig. 2 (a) Bending GND electrode within the varactor cell and creation of parasitic capacitances,
(b) Avoiding of further parasitic capacitances.

Another aspect to consider with parasitic capacitances is a type of cross-coupling effect. The electrodes that create the varactor capacitance are located at different levels within the layer stack. To avoid additional cross-coupling, only the active area between the GND electrode and the HF line may overlap. To achieve this, both paths should run perpendicular to each other, for example as shown in Fig. 3.

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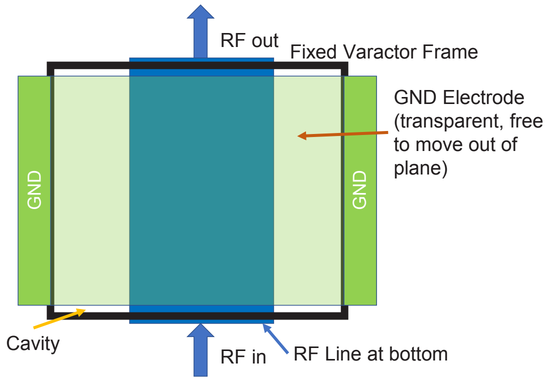

Fig. 3 Reduction of parasitic capacitances by crossing the GND and RF line (top view without drive electrode).

RF-Challenges

RF challenges for MEMS varactors primarily revolve around maintaining a high quality factor (QF) and a consistent capacitor value at the device's operating frequency f. Operational challenges include the need to operate the MEMS varactor well below its resonance frequency f_0 to ensure a stable capacitance at the desired frequency.

Achieving a constant capacitor value throughout the operating frequency range poses a significant challenge due to its frequency-dependent parasitics, particularly near resonance. Additionally, managing the nonlinear behavior in RF MEMS varactors, characterized by variations in capacitance slope with actuation voltage (V_a) changes, results in inefficient use of DC voltage.

The QF of the MEMS varactor can be determined using the expression in equation (8) under the assumption that the operating frequency is significantly lower than the resonance frequency ($f \ll f_0$).

$$QF = -\frac{\Im(Z_{eq})}{\Re(Z_{eq})} = \frac{1}{2\pi f C}\left[\frac{1}{R_{eq}}\right] \qquad (8)$$

with

$\Im(Z_{eq}) = X_{eq}(-1/\omega C)$, for $\Im(Z_{eq}) < 0$

Where Z_{eq} is the effective impedance of the MEMS varactor approximated from π- or t-network. The Z_{eq} is a function of return S_{11} and insertion loss S_{21} assuming symmetry and reciprocity. Hence the effective resistance should be kept low as much as possible to improve the device QF. If we consider the QF at C_{max} (i.e., QF_1 with no actuation voltage applied), then the tuning ratio (TR) of the MEMS varactor is connected with:

$$QF_1 = \frac{1}{2\pi f C_{min} TR}\left[\frac{1}{R_{eq}^1}\right] \qquad (9)$$

The TR can be improved by maximizing C_{max} and/or minimizing C_{min}. However, from the factor $f C_{min} TR$ or $f C_{max}$ if we maximize C_{max} then the frequency will have to decrease to achieve a higher QF else the QF at C_{max} will deteriorates. The design choice hinges on the device's operational frequency. For higher frequencies, it's optimal to minimize C_{min}, while at lower frequencies, maximizing C_{min} is preferable. Ideally, the highest TR occurs when C_{max} is maximized and C_{min} is minimized. In practice, achieving this means designing a MEMS varactor with a broad frequency range but lower QF in most of the operating band.

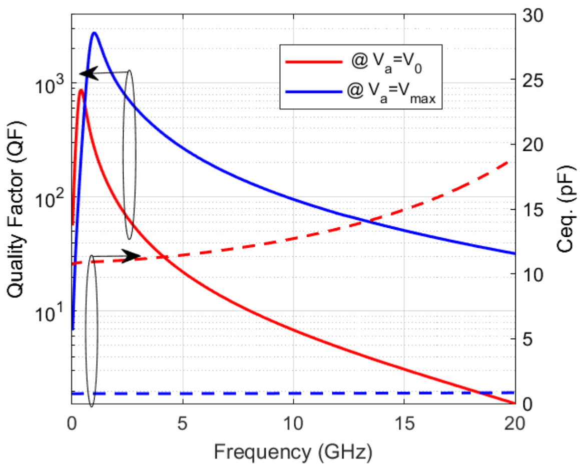

Fig. 4 EM simulated result for the MEMS varactor structure (excluding the drive electrode effect) comparing the changes in the quality factor (solid lines) and equivalent capacitor values (dashed lines) for two actuation states resulting in C_{min} and C_{max} that affects the TR.

The bridge MEMS varactor (without drive electrode) shown in Fig. 3 above achieved good TR of 14 ($C_{min} = 0.77$ pF and $C_{max} = 10.94$ pF at 500 MHz) and large QF from the HF electromagnetic simulation results.

In Fig. 4 the QF and the corresponding extracted equivalent capacitance are plotted. Notably, the MEMS varactor exhibits a nearly constant behavior, with variations of less than 10% across the frequency band of 0.5…6 GHz. At 6 GHz, considering the series inductance of the device, the QF reaches a substantial value of 204 at $V_a = V_{max}$ and about 20 at $V_a = V_0$ (no actuation).

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Fabrication Approach and Proposed Design

The structures shown schematically in Fig. 1 can be manufactured using surface micromachining methods. Similar processes are used as in the production of integrated circuits, such as deposition, photolithography, dry and wet etching, CMP (chemical-mechanical polishing), etc. With the sacrificial layer technology, freely hanging structures, such as a movable GND electrode, can be realized. Typically, this involves a sequence of additive and subtractive manufacturing steps that must be repeated several times to produce the entire structure.

With the help of FEM simulations, optimal technologically feasible geometries were examined, and the theoretically achievable tuning ratios were determined. A highly simplified schematic representation of the key steps is shown in Fig. 5

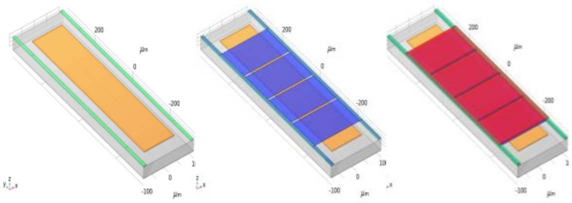

Fig. 5 Technologically key steps for fabrication of the bridge-varactor: deposition and structuring of RF-line, deposition of the GND-electrode over RF-line, deposition of a driving electrode.

The silicon substrate (grey) should be electrically insulated e. g. via thermal oxidation. The metal layer (yellow), such as aluminum or gold or their alloys, could be deposited on top of the oxide using for example PVD and structured by dry etching. For a high initial capacitance, the distance between the RF-line and the GND-electrode should be minimized. Therefore, the sacrificial layer must be thin and conformal. This can be achieved by atomic layer deposition of the sacrificial layer with a thickness of tens of nanometers. Different materials could act here as a sacrificial layer.

On top a second metallization (blue) follows. During the shaping phase of the GND-electrode additional slits should be made for a secure removal of the sacrificial layer. The number of slits as well as their width, however, depends on the dimension of the GND-electrode. The first part is done and can be covered with protecting oxide layer.

After it has been structured and planarized using CMP, the structuring of the second level can begin. The technological sequence is similar to the first part, except that the sacrificial layer between the GND- and drive-electrode (red) must be significantly larger in order to allow enough stroke and thus a larger capacity reduction. In the final metallization step, bond pads and routings are structured in the periphery. After the stack is finished the final release take place, during which the sacrificial layer is removed typically by the etching gas. To achieve this, the gas must be easily accessible to all sacrificial layer locations. At the end of the process, the bridge-varactor is created, which cross-section could be seen in the Fig. 6.

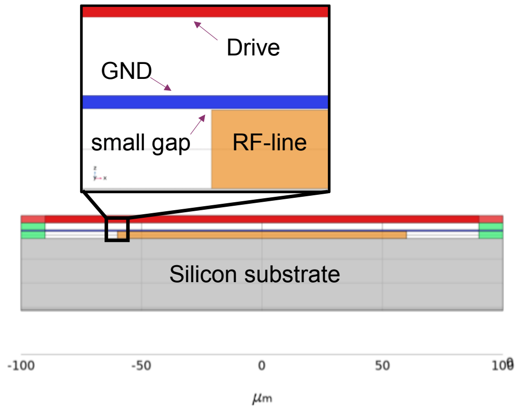

Fig. 6 Cross-sectional view of the designed bridge-varactor with reduced parasitic capacitances

Conclusions

When designing the MEMS-based varactors, various aspects aimed at maximizing the tuning ratio should be taken into account. This not only includes the correct selection of effective actuator systems and suitable materials with low RF losses, but also the entire system must be analyzed, and the influence of all individual components must be harmonized. By suppressing the influences of parasitic capacitances, it is possible to develop MEMS varactors with tuning ratios greater than ten. This not only meets the requirements of today's high frequency applications, but also exceeds the capabilities of modern semiconductor components.

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