1

Introduction

This book is focused on the design and characterization of integrated varactors. A varactor is a voltage-variable capacitor; in other words, the value of its capacitance changes in accordance with the voltage applied to it.

Chapter 1 looks at the general concepts of an integrated varactor. Chapter 2 analyses the operating principle of integrated PN-junction varactors and the tools used for their design. Chapter 3 continues along the same lines and looks at MOS varactors.

After the different types of varactors have been analysed, Chapter 4 offers a method for their characterization, Chapter 5 looks at the models of varactor and Chapter 6 gives details of the design rules resulting from the work of the previous chapters.

Finally, Chapter 7 presents the design of different circuits that use varactors for correct operation, including the design of a voltage-controlled oscillator with a varactor in its LC tank.

1.1 PASSIVE ELEMENTS

As a varactor is a voltage-variable capacitor, varactors are passive elements. A passive element is one that can only store or dissipate energy. An active element is one that provides energy to the signals travelling through it.

Passive elements can be separated into two large groups: linear elements and non-linear elements. Linear passive elements mainly include resistors, inductors, capacitors and transformers, which either dissipate or store energy. Non-linear elements mainly include diodes and varactors. Diodes are characterized by their I–V curve and varactors by their C–V curve and varactors are the subject matter of this book.

Design and Characterization of Integrated Varactors for RF Applications Í. Gutiérrez, J. Meléndez and E. Hernández

Desoer (1969) gives a defining inequation of passive components. A one-port element with a voltage $v(t)$ and a current $i(t)$ is said to be passive when it fulfils the following equation:

$$\int_{t_0}^{t} v(t) \cdot i(t) \cdot \mathrm{d}t + \varepsilon(t_0) \geq 0 \tag{1.1}$$

where $\varepsilon(t_0)$ is the energy stored by the element at the instant t_0.

To analyse the passivity of an element at high frequencies, it is more appropriate to analyse the S-parameter matrix when energy is applied to one of its ports (Carlin, 1964). The power dissipated on one of the ports of the element is given by:

$$P_k = P_{\mathrm{i}k} - P_{\mathrm{r}k} \tag{1.2}$$

where the subscript i indicates incident power and r indicates reflected power. In terms of reflected waves (**b**) and incident waves (**a**), we have the following:

$$P_k = a_k \cdot \bar{a}_k - b_k \cdot \bar{b}_k \tag{1.3}$$

where $\bar{a}_k$ and $\bar{b}_k$ represent the conjugate of the incident and reflected waves on port k, respectively. The sum of the powers of all the ports gives the following:

$$P = \sum_{k=1}^{\mathrm{n}} P_k = \bar{a}^{\mathrm{T}} \cdot a - \bar{b}^{\mathrm{T}} \cdot b. \tag{1.4}$$

By the definition of S-parameters, the vector b is equal to S·a, where S represents the S-parameter matrix. Then:

$$\mathrm{P} = \bar{\mathrm{a}}^{\mathrm{T}} \cdot \mathrm{a} - \bar{\mathrm{a}}^{\mathrm{T}} \cdot \bar{\mathrm{S}}^{\mathrm{T}} \cdot \mathrm{S} \cdot \mathrm{a} = \bar{\mathrm{a}}^{\mathrm{T}}(\mathrm{I} - \bar{\mathrm{S}}^{\mathrm{T}} \cdot \mathrm{S}) \cdot \mathrm{a} = \bar{\mathrm{a}}^{\mathrm{T}} \cdot \mathrm{Q} \cdot \mathrm{a} \tag{1.5}$$

where Q is the dissipation matrix. Mention must be made of the fact that:

$$\bar{\mathrm{Q}}^{\mathrm{T}} = \bar{\mathrm{I}}^{\mathrm{T}} - (\bar{\mathrm{S}}^{\mathrm{T}} \cdot \mathrm{S})^{\mathrm{T}} = \mathrm{I} - \bar{\mathrm{S}}^{\mathrm{T}} \cdot \mathrm{S} = \mathrm{Q} \tag{1.6}$$

Therefore, it can be said that the matrix Q is a Hermitian matrix. By the definition of passivity:

$$\mathrm{P} = \bar{\mathrm{a}}^{\mathrm{T}} \cdot \mathrm{Q} \cdot \mathrm{a} \geq 0. \tag{1.7}$$

Therefore, if the matrix Q is positive defined or positive semi-defined, the S-matrix corresponds to a passive network. This last condition can be deduced intuitively (Niknejaud, 2001). The elements of the S-matrix diagonal represent the reflection coefficients when the remaining ports are matched. The other components of the matrix represent the transmission coefficients under matching conditions.

On a passive network, the conservation of energy implies that the reflected and transmitted power on one of the ports must be less than or equal to the incident power. In other words, all the elements of the matrix must have a value that is equal to or less than the unit.

1.2 FIGURES OF MERIT OF VARACTORS

The two most important figures of merit in the case of varactors are the quality factor (Q) and the tuning range (TR). Other parameters of importance include the self-resonant frequency, maximum capacitance and the effective silicon area.

1.2.1 Quality Factor

The quality factor measures element behaviour taking into account both stored and lost energy. The most common definition of the quality factor is the ratio between the absolute value of the negative imaginary part and the real part of the reflection parameter y_{11} (Ashby *et al.*, 1996; Molnar *et al.*, 2002).

$$Q = \frac{|\mathrm{Imag}(y_{11})|}{\mathrm{Re}(y_{11})} \tag{1.8}$$

The value of y_{11} is obtained from the S-parameters of the passive element, in this case, a varactor. The imaginary part of the reflection parameter represents the energy stored in the passive element, whereas the real part is the dissipated energy. Therefore, the quality factor can be defined as per Equation (1.9):

$$Q = 2\pi \frac{|\text{stored inductive } E - \text{stored capacitive } E|}{E \text{ lost per cycle}}. \tag{1.9}$$

In accordance with Equation (1.9), the best results are obtained by minimizing the losses and making the energy stored by the device as great as possible. In this case, these energies are defined by maximas. If the varactor operates on a frequency that is remote from the resonance frequency, the stored inductive energy is insignificant:

$$Q = 2\pi \frac{\text{stored capacitive } E}{E \text{ lost per cycle}} = 2\pi \frac{E_{C\max}}{E_{\text{dis}}}. \tag{1.10}$$

The maximum energy stored in a varactor is defined as:

$$E_{C\max} = \frac{1}{2} C_p V_p^2 \tag{1.11}$$

where V_P is the maximum voltage and C_p is the capacity of the varactor.

The energy lost per cycle E_{dis} will take different expressions depending on the simplified model of the varactor used, as shown below.

1.2.2 Tuning Range

The tuning range can be considered the most important parameter regarding the varactor functionality. The variation range of the capacitance of a specific varactor is defined as the ratio between $C_{\max}$ and $C_{\min}$, where $C_{\max}$ and $C_{\min}$ are the maximum and minimum capacitances, respectively.

The aim is to achieve a wide capacitance variation range when working with a wide range of voltages. The tuning range is calculated as $C_{\max}/C_{\min}$ or using the equation (Hernandez, 2002):

$$TR = \pm \frac{\frac{1}{2}\frac{C_{\max} - C_{\min}}{C_{\max} + C_{\min}}}{2} = \pm \frac{C_{\max} - C_{\min}}{C_{\max} + C_{\min}} \tag{1.12}$$

1.2.3 Self-resonant Frequency (f_{R})

In principle, the behaviour of a varactor could be represented by the circuit shown in Figure 1.1; however, at high frequencies this circuit is not appropriate. The circuit in Figure 1.1 includes an inductor in series which takes into account the parasite inductance of the interconnection lines used in the varactor.

In integrated varactors, the inductance value (L_s) is very low; however, at high frequencies, the said inductance can enter into resonance with the resistance in parallel and the variable capacitance and cancel its value. Obviously, the f_{R} must be as high as possible to avoid the incorrect functioning of the varactor. As the capacitance is variable, the resonant frequency (f_{R}) is a function of the supply voltage. To obtain a constant reference value, the f_{R}

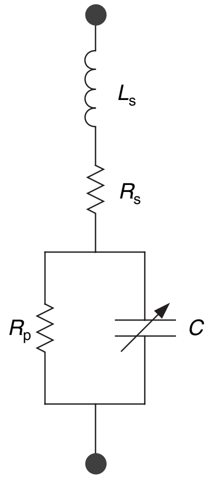

Figure 1.1 Simplified equivalent circuit of a varactor at high frequencies.

corresponding to the minimum voltage value is usually taken (where it reaches C_{max}) (Pedersen, 2001).

1.2.4 Effective Silicon Area

This parameter is measured in terms of capacitance by unit of area, where the typical unit is fF/μm^2. The objective is to obtain a high effective silicon area as it may represent a considerable reduction in cost by reducing the size of the device (Aparicio and Hajimiri, 2002).

1.2.5 Absolute Capacity Value

In the case of discrete designs, varactors are classified in accordance with their absolute capacitance value; each class is labelled with its corresponding useful frequency range. However, with integrated varactors, the capacitive properties are measured in terms of the C_{max}/C_{min} ratio. Therefore, only one of the two values (C_{max} or C_{min}) needs to be specified.

1.3 PRINCIPAL TYPES OF VARACTOR MANUFACTURE

1.3.1 Discrete Varactors

Owing to the lack of integrated varactors of acceptable quality, designers are forced to use discrete varactors. Figure 1.2 shows an example of a set

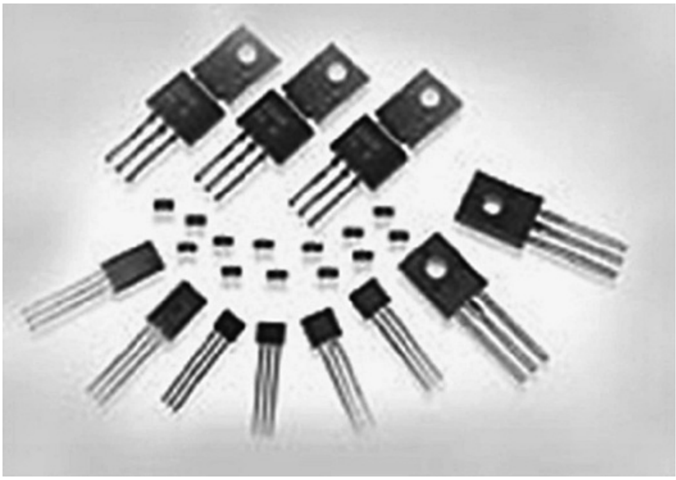

Figure 1.2 Non-integrated varactors.

of non-integrated varactors with external connections. The use of discrete varactors requires the use of connections that are external to the circuit. This increases the size of the system and involves uncertainty as to the parasite effects of the said connections. However, the quality factors are very high.

1.3.2 MEMS Varactors

Another alternative for the manufacture of varactors is a micro-electromechanical system (MEMS). A MEMS is a miniaturized intelligent microsystem that integrates the sensor functions of process and/or action. The MEMS for RF, which includes varactors, uses air as dielectric material due to its lower losses in the RF frequency range, leading to very high quality factors Q. A surface micromachining process is commonly used to fabricate MEMS tunable capacitors.

The present manufacture of MEMS varactors involves many lines of construction:

- MEMS varactors based on the micro-machining of volume and a subsequent sticking process (Xiao *et al.*, 2003);
- MEMS varactors using copper as sacrificial layers (Zou *et al.*, 2001);

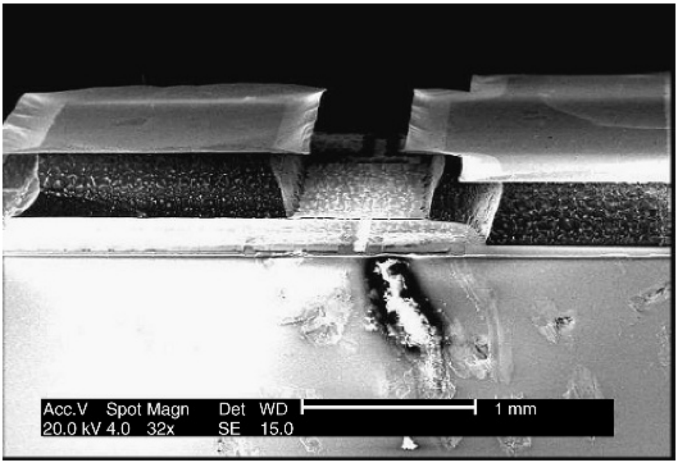

Figure 1.3 MEMS varactor (Etxeberria *et al.*, 2005).

- MEMS varactors using nickel and gold as structural materials for the suspended plates and titanium as a sacrificial layer material (Gallant and Wood, 2004);
- MEMS varactors that use silicon wafer and pyrex wafer and developed by an anodic bonding process. Figure 1.3 shows a microphotograph of a varactor that is based on the reactive ion etching of silicon wafer and anodic bonding of silicon and pyrex wafers (Etxeberria *et al.*, 2005).

Although MEMS varactors have very high quality factors, they have two significant disadvantages: as they are not manufactured using a standard technology, the manufacturing cost is high and they also require connections external to the circuit.

1.3.3 BST Varactors

These varactors are developed using the nonlinear dielectric tuneability of barium strontium titanate (BST) thin films. The goal of integrating passive thin films components with a BST varactor is to allow the development of extremely low-cost microwave components. The BST material was grown on c-plane sapphire substrate using RF magnetron substrate. The films were sputtered from multiple ceramic targets consisting of varying ratios of barium and strontium (Chase *et al.*, 2005).

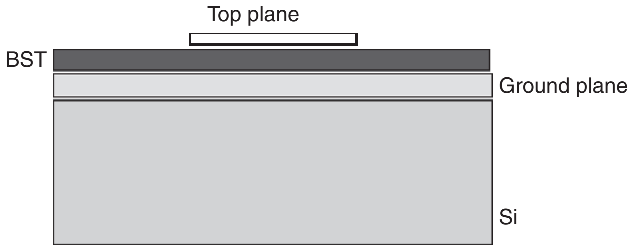

Figure 1.4 BST varactor.

The principal applications of these varactors are:

- tuneable band-pass filters;
- impedance matching networks;
- voltage control oscillators (VCOs).

Figure 1.4 shows the schematic section of a BST varactor.

1.3.4 Integrated Varactors Using Standard Technologies

There is much interest in the optimization of integrated varactors using standard CMOS, BiCMOS and SiGe manufacturing technologies with acceptable levels of quality, since this would enable RF designers to improve the performance levels of their RF circuits.

Integrated varactors are passive components with a wide range of applications in the field of radio-frequency communications (RF). Depending on the type of application, the geometry of the varactors differs, giving rise to various classes of integrated varactors. This type of varactor is examined as follows.

References

Aparicio, R. and Hajimiri, A. (2002) Capacity limits and matching properties of integrated capacitors. *IEEE Journal of Solid State Circuits*, **37**(3), 384–393.

Ashby, K. B. *et al.* (1996) High *Q* inductors for wireless application in a complementary silicon bipolar process. *IEEE Journal of Solid-State Circuits*, **31**, 4–9.

Carlin, H. J. (1964) *An Introduction to Reciprocal and Non-reciprocal Circuits*, Prentice-Hall, Englewood Cliffs, USA.

Chase, D. R. *et al.* (2005) Modeling the capacitivity nonlinearity in thin film BST varactors. *IEEE Transactions on Microwave Theory and Techniques*, **53**(10), 3215–3220.

Desoer, C. A. (1969) *Basic Circuit Theory*, McGraw Hill, New York, USA.

Etxeberria, J.A. *et al.* (2005) Ultrathin metallic membranes to be used in tuneable RFMEMS volume capacitors. *Proc. IEEE Sensor*, **1**, 448–451.

Gallant, J. and Wood, D. (2004) The role of fabrication techniques on the performance of widely tuneable micromachined capacitors. *Sensor and Actuators*, **A110**, 423–431.

Hernández, E. (2002) Integration of a TV frequency converter for SiGe 0.8 μm technology. Ph.D. Thesis, Tecnun, University of Navarra, Spain.

Molnar, K. *et al.* (2002) MOS varactor modeling with a subcircuit utilizing the BSIM · v3 model. *IEEE Trans. Electron Devices*, **49**, 1206–1211.

Niknejaud, A. M. (2000) Analysis, simulation and applications of passive devices on conductive substrates. Ph.D. Thesis, Berkeley, California, USA.

Pedersen, E. (2001) RF CMOS varactors for wireless applications. Ph.D. Thesis, Aalborg, Denmark.

Xiao, Z. *et al.* (2003) Micromachined variable capacitors with wide tuning range. *Sensors and Actuators*, **A104**, 299–305.

Zou, J. *et al.* (2001) Development of a wide-tuning-range two-parallel-plate tunable capacitor for integrated wireless communication systems. *International Journal of RF and Microwave Computer Aided Engineering*, **11**(5), 322–329.