1. INTRODUCTION

Piezoelectric crystals, ceramics, polymers, and piezocomposite materials have long dominated the ultrasonic transducer technology, especially in medical ultrasound imaging. In recent years, thanks to the advances in microfabrication techniques, the technology of capacitive Micromachined Ultrasonic Transducers (CMUTs) has emerged as a competitive technology in the field of medical imaging.

The principle of operation is the well-known electrostatic transduction mechanism. The basic element of a CMUT is a capacitor cell with one fixed electrode (backplate) and the second one supported by a flexible membrane that can vibrate. If an alternating voltage is superimposed to the bias voltage, applied between the membrane and the backplate, the modulation of the electrostatic force results in the vibration of the membrane with subsequent generation of ultrasounds at the same frequency of the modulation. Conversely, when the biased membrane is subjected to an incident ultrasonic wave, the change of the capacitance, due to membrane vibration, can be detected. The idea of generating acoustic waves utilizing the electrostatic attraction force between the plates of a condenser is as old
as the early piezoelectric transducers [35]. However, only in the early 1990s the development of micromachining technology allowed to fabricate electrostatic transducers consisting of a large number of membranes with precisely controlled dimensions, in the order of tens of microns for operation in the megahertz range [20]. The electrode separation, with this technology, can be made very narrow, in the sub-micron range, enabling high electric fields inside the gap, that result in high transduction efficiency and sensitivity.

CMUTs are fabricated onto silicon wafers by means of silicon micromachining techniques, using standard IC fabrication processes. This makes possible the realization of large 1-D and 2-D transducer arrays by choosing the proper photolithographic masks. 2-D arrays with a large number of elements are suitable for real-time 3-D medical imaging, which is an important topic of current research, as it will be illustrates in Sec. 4.1. There are two main limitations in designing volumetric imaging systems with conventional 2-D piezoelectric arrays: the low acoustic power output and the receive sensitivity because of the small size of the elements; and the difficulty to provide individual electrical connections to each element [48]. CMUT technology has shown to be a good candidate to overcome these challenges, and the first 2-D CMUT arrays having $128 \times 128$ elements, electrically connected by through-wafer interconnects, have been successfully fabricated and characterized [10].

Other important advantages of CMUTs, compared to the current piezoelectric transducers, are the wider immersion bandwidth, that results in improved image resolution, low noise, and the potentiality to be integrated with electronic circuits on the same wafer. The broad bandwidth of CMUTs also enables other imaging modalities, such as tissue harmonic imaging, in which energy is transmitted at a fundamental frequency, and an image is formed with the energy at the second harmonic [1]. Finally, thanks to their miniaturization, CMUTs are also promising for high-frequency applications, such as intravascular ultrasound imaging (IVUS). Other potential applications include air-coupled non-destructive evaluation [21], ultrasonic flow meters for narrow gas pipeline [14], microphones with RF detection [22], Lamb wave devices [64], and smart microfluidic channels [27].

This chapter is divided in three sections. The first section focuses on the modeling of electrostatic transducers, reporting first an analytical model for the single electrostatic cell and then for the whole micromachined ultrasonic transducer. The second section gives an overview of the fabrication processes developed in the last decade to manufacture CMUTs, addressing process issues, such as the choice of materials for process compatibility and reliability. The third section winds up with the description of the CMUTs’ potential applications, of which medical imaging has been successfully demonstrated.

2. CMUT MODELING

2.1. Analytical Modeling of the Single Electrostatic Cell

Basic CMUT analytical modeling is based on the traditional equivalent circuit for capacitive transducers developed by Mason [40], which is valid under small signal conditions, i.e. for linear operation.