Fabrication and experimental characterization of capacitive micromachined ultrasonic transducers made with anodic-bonding technology

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Capacitive micromachined ultrasonic transducers CMUTs introduced about two decades ago have been shown to be a good alternative to conventional piezoelectric transducers in various aspects, such as sensitivity, transduction efficiency, bandwidth etc…

CMUT arrays are commonly fabricated by means of surface micromachining or wafer bonding techniques. Surface micromachined cMUTs have a common drawback, i.e., their electrode gap may not be made too large. Otherwise the deposition period of the sacrificial layer will be unacceptably long. Small electrode gap itself does not constitute problem to transducer operation, but it does influence its fabrication, because the vibrating membranes are usually released by wet etching process, whereas in small distance range, capillary force plays an important role. Another problem is its inferior surface flatness. Surface micromachining consists of successive deposition and patterning. During this procedure, the wafer's surface will repetitively be modified. Unless extra planarization steps are introduced, the surface topology can never be flat. Such unevenness is also disadvantageous to the uniformity of the transducer [1]. Direct bonding places stringent requirements on the cleanliness and flatness of the surfaces to be bonded and it requires a high temperature annealing to establish high strength bonding [2]. To realize reliable bonding, the contact areas roughness should not exceed 1~2nm, and the wafer flatness should be smaller than 2µm. Furthermore, to avoid bonding voids, no particles should be present on the wafer's surface [1]. Moreover, the use of a silicon wafer as mechanical support of the transducer is not optimal for the device operation, as it generates ringing in the pulse-echo signal because of its high acoustic impedance [3]

To solve these drawbacks, a CMUT transducer has been designed and realized using a new fabrication process called anodic bonding introduced in [6]. It's a particularly promising technique for CMUTs technology because it does not require either a postheat treatment at high temperature or hydrophilic cleaning. Moreover, it's easy and reliable to control and requires no expensive installation. Glass-to-silicon stacks are commonly applied because of the ease of bonding with high alignment accuracy due to glass transparency. Anodic bonding offers advantages of high bond strength at moderate or low processing temperature, usually lower than the glass softening point and the melting points of the materials selected for this purpose (200°C–400°C). Thus, materials with large differences in the thermal expansion coefficient can be bonded together with better reliability. The use of low temperature for bonding can avoid damaging pre-fabricated devices and integrated circuitries. In comparison with direct bonding, the surface quality requirement of anodic bonding is much tolerant and does not require an ultraclean environment. In fact, even if a 1~2µm high step exists on the interface, realization of anodic bonding is still possible [1]. Other advantages of glass to silicon bonding are the benefits of the electrical, thermal and optical properties of the glass. The glass provides dielectric isolation properties that significantly reduce parasitic capacitance in capacitance transducers (compared with silicon/silicon bonding). In manufacturing, the glass optical transparency enables backside and internal state visual inspections and optical diagnostics of the sealed microstructures [4]

Here, we introduce a new process to the CMUTs technology that uses the anodic-bonding technique to fabricate membranes of silicon on a glass wafer for acoustic applications. This new design, based on silicon-on-insulator SOI anodic bonding technology utilizes a structured glass as well as a highly doped and, therefore, conductive membrane of SOI silicon. This new technology enables the fabrication of large membranes with large gaps, and can expand the frequency span of the CMUTs to a low frequency operation range. Moreover, anodic-bonding-based CMUT fabrication as its wafer-bonding counterpart provides design flexibility in terms of choice of materials and fabrication of membranes with different thickness profiles.

After introducing the basic operating principles of the anodic bonding technique, we will provide a brief description of the design process as an alternate method of CMUTs technology that utilizes a glass wafer as a frame and SOI silicon as a membrane. The designed cells have a diameter varying from 50µm to 150µm and a cell to cell pitch decreasing from 150µm to 20µm. The element to element pitch is defined to be less than half of the wavelength of the acoustic ultrasound wave for each designed cell. The ratio between the bottom electrode radius and the cavity radius is 80%, which represents a surface fill factor of 64%. The performance of the CMUT transducers is evaluated by demonstrating basic characterization results and their relevance to the device performance in order to determine the yield and the uniformity of the anodic bonding process. It involves laser-vibrometry as well as electrical impedance measurements

The vibration behaviour of CMUT individual cells and arrays was investigated using a laser vibrometer coupled to a displacement decoder. The impulsional response of each cell was measured (under AC+DC excitations) and its spectral response deduced, allowing us to extract its band width directly as well as its fundamental resonance frequency and first harmonics and compare them with theoretical predictions based on circular membrane models from FEM and analytical simulations. The measured spectral response was confirmed by making a frequency sweep excitation from 30KHz to 20MHz for every tested cell. To eliminate the effect of acousto-optic interaction and calibrate the displacement decoder, the laser beam was initially focused on the posts of the cells where the actual displacement would be negligible in comparison to that of the cells as well as on a static flat polished silicon wafer. Assuming the posts and the flat wafer to be fixed, the interferometer data gathered was later used to correct for the actual membrane displacements [5]. CMUT devices with different frequency spans were fabricated using this technology, and tested. These devices have been applied to a displacement measurement in air. So far, cMUTs single cells and arrays have been produced with resonance frequencies in the range from 290Khz to 2.4MHz. Peak displacement levels varied approximately between 1nm to 35nm for the 50µm cells and between 5 to 35nm for the 150µm cells. Several over-responsive and under responsive elements could be seen as well as a non-responsive element. The locations of the under- and over-responsive elements were random in nature. The most likely explanation for these measured differences is due to variations in the CMUT membrane characteristics (residual stress, thickness, bonding quality to support).

The visualization, analysis of surface topography (static and dynamic) and structural vibration patterns (dynamic) of the CMUT individual cells/arrays have been investigated using the MS-500 Polytec MEMS analyzer. The resulting vibration maps gave us important informations about the static and dynamic mechanical behavior of cMUTs. In particularly, these helped us in quantifying the anodic bonding quality regarding the resulting curvature (tensile-compressive strain) and the initial deflection of the membrane due to the vacuum bonding.

The CMUT cells and arrays were also electrically characterised in air using a capacitor meter and vector network analyzer in order to obtain the electrical resonance frequency and bandwidth. Input electrical impedance in air was measured as a function of frequency. The electro-mechanical coupling factor evaluation was based on capacitance determination and, the resulting resonance and antiresonance peaks.

Initial investigation results showed that, this newly developed CMUT has the advantages of relatively uniform cavity definition and membrane bonding with reliable vibrational behavior for acoustic applications

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