Progress in Silicon Microphones

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Abstract: Silicon microphones have recently been improved in a number of ways. Examples are the invention of new operational principles, the use of advanced materials, improved micromachining technologies, extension of frequency and dynamic ranges, increase of sensitivity and signal-to-noise ratio, and better understanding of the operation. Progress in this field, achieved over the past three years in a number of laboratories, is discussed.

INTRODUCTION

Silicon microphones were first described in 1983 [1, 2]. In the meantime, the field has been very active with numerous reports on condenser, piezoelectric, piezoresistive, modulated FET, and optic-waveguide transducers published in the literature [3]. As shall be discussed, a number of new or improved designs have recently been suggested and the understanding of these devices has been improved.

CONDENSER MICROPHONES

Considerable progress has lately been made in the electret biasing of condenser microphones by using charged membranes consisting of silicon oxide-silicon nitride double layers [4]. These layers have much better charge stability than $SiO_2$ films [4, 5] and are also nearly stress compensated, making them more pliable than $Si_3N_4$ membranes with their high tensile stress. Microphones with the charged double layers are now undergoing testing.

Another new approach to electret biasing of silicon microphones consists in the spincoating of a nitride membrane with a 1 $\mu$m Teflon AF layer and subsequent charging [6]. As opposed to fabrication processes utilizing glued-on Teflon films, this technology is fully compatible with silicon micromachining.

For minimal noise, condenser microphones require on-chip preamplification or impedance conversion. To alleviate the problems encountered by performing microphone and circuit processing on the same chip, a technology utilizing a polyimide (PI) microphone structure has been used [7]. The microphone is a one-chip device consisting of a 18 $\mu$m thick PI backplate and a 1 $\mu$m PI membrane, separated by a 1.5 $\mu$m air gap obtained by a sacrificial-layer process. It has a sensitivity of 8 mV/Pa and an equivalent noise level of 24 dB(A).

Several other single-chip capacitive microphones have been described [8] - [10]. One-chip technology avoids the problems of chip-bonding and adjusting.

The understanding of condenser microphones was advanced by theoretical papers dealing with the effects of viscosity and heat conduction in the air gap [11], with the electromechanical behaviour of thin perforated backplates [12], and with nonlinear effects causing harmonic distortion [13].

PIEZOELECTRIC AND -RESISTIVE MICROPHONES

Piezoelectric microphones were made with inorganic and organic piezomaterials. The highest sensitivities of broadband transducers (frequency range at least 10 kHz) of about 1 $mm^2$ area were 0.74 mV/Pa open circuit with corresponding equivalent-noise levels of 44 dB [14]. Sensitivities for series-connected microphones on a single chip are somewhat higher [15]. With narrower-bandwidth, cantilever-type microphones of 4 $mm^2$ area, sensitivities of 3 mV/Pa have been obtained [16].

Piezoresistive microphones were built with mono- and polycrystalline silicon as the piezoresistive layer [17]. The low-impedance, active devices work in a Wheatstone-bridge circuit using bias voltages of about 10 V. Highest sensitivities of microphones with monocrystalline silicon and a membrane area of 1 $mm^2$ are about 0.45 mV/Pa with an equivalent noise level of 43 dB(A). The polycrystalline sensors have smaller sensitivities.

ULTRASONIC TRANSDUCERS

A large number of micromachined ultrasonic transducers for airborne and waterborne sound have recently been described. At high frequencies, the radiation impedance and directivity of the small silicon transducers is such that they can also be used as transmitters.

Capacitive transducers for airborne sound have been designed for the ultrasonic range up to about 10 MHz, both as single microphones and as microphone arrays [18] - [21]. The transducers for frequencies below 1 MHz use perforated backplates for increased sensitivity [18]. In this case, the damping due to resistive air flow in the thin
air gap has to be controlled by proper dimensioning of gap thickness and hole spacing. The higher frequency devices require large restoring forces and can therefore operate with a flat or grooved backplate [19, 20]. Two-dimensional arrays for the frequency range up to 200 kHz, which yield directional sensitivity, have also been realized [21]. A new kind of ultrasonic generator utilizes electrothermal excitation of a silicon membrane resonator [22]. Such transducers were integrated with a piezoresistive microphone on the same membrane to form a microsystem for ultrasonic object detection.

Ultrasonic silicon transducers for waterborne sound use either the piezoelectric or the capacitive principle. A new piezoelectric pulse-echo device, operating in the medical ultrasonic range, consists of a silicon membrane with a covering layer of Poly(vinylidene fluoride-trifluoroethylene) [23]. The transducer delivers pulses of about 10 ns length and achieves a dynamic range of 40 dB and an insertion loss of 48 dB in pulse-echo operation. Other piezoelectric hydrophones use sol-gel PZT-layers on micromachined silicon wafers [24]. These transducers, designed as arrays with 8 x 8 elements, operate in the frequency range 0.3 to 2 MHz and have been used for imaging sonar.

Capacitive transducers for underwater ultrasonics were recently made on silicon wafers in the form of fixed arrays with up to 30 x 30 elements, combined with CMOS transistors for signal amplification [25, 26]. Single elements have hexagonal membranes of 40 µm sidelength with resonance frequencies of about 8 MHz. These transducers were designed for medical imaging.

**References**