Wideband micromachined acoustic sensors with radio frequency detection

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ABSTRACT

Silicon micromachining techniques permit batch fabrication of microphones that are small, reproducible, and inexpensive. However, many such sensors have limited bandwidth or are too fragile to be used in a humid, wet, or dusty outdoor environment. Microphones using capacitive micromachined ultrasonic transducer (CMUT) membranes and radio frequency (RF) detection overcome some of the problems associated with conventional micromachined microphones. CMUT membranes can be vacuum-sealed and still withstand atmospheric pressure and submersion in water. In addition, the membrane mechanical response is very flat from dc up to hundreds of kilohertz. A very sensitive RF detection scheme is necessary to detect the small changes in membrane displacement that result from utilizing smaller membranes. In this paper, we present the theory and recent experimental results of RF detection with CMUT membranes. Measurements of a sensor with 1-mm^2 area demonstrate a flat output response of the acoustic sensor from a fraction of 1 Hz to over 100 kHz, with a sensitivity at 1 kHz of 65 dB/Pa in a 1-Hz noise bandwidth.

Keywords: RF detection, microphone, micromachined, CMUT, acoustic, ultrasonic, transducer

1. INTRODUCTION

The demand for sensitive microphones, coupled with advancements in micromachining technology, has led to the development of many miniature acoustical pressure sensors.[1] Micromachining and lithography techniques permit very accurate control of dimensions, yielding reproducible sensors while offering the prospect of inexpensive, mass-produced devices. Most of these microphones are based on a capacitive (or condenser) microphone design, with one or more capacitive membranes responding to acoustic pressure.

The development of miniature microphones primarily has focused on hearing aid applications, and therefore concentrates on acoustic detection only in a limited audio range.[2] However, many industrial and military applications require acoustic data collection over larger bandwidths for proper signal identification, with particular attention to frequencies below 200 Hz. Low-frequency detection below the audio range is useful for condition-monitoring applications for heavy equipment and engines[3] as well as target acquisition.[4] For operation in harsh environments, such as the battlefield, an acoustic sensor also should be impervious to dust and moisture and have a large dynamic range to measure a wide range of sound pressure levels. This paper describes the basic theory and experimental results for a robust, miniature microphone for measuring broadband acoustic signals near dc up to 100 kHz.

2. CAPACITIVE TRANSDUCERS

2.1. Micromachined Microphones

Capacitive microphones or transducers consist of one or more conductive diaphragms suspended over a conductive backplate, as shown in Fig. 1. Sound detection is possible when the impinging pressure vibrates the diaphragm, thus changing the capacitance of the transducer. For conventional microphones, the change in capacitance is detected by measuring either the output current under constant-voltage bias or the output voltage under a constant charge on the diaphragm electrode. Typically, if the membrane is larger than 1–2 mm in size, a pressure equalization vent in the backchamber prevents any fluctuations of atmospheric pressure from collapsing the membrane against the backplate.

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Unattended Ground Sensor Technologies and Applications V, Edward M. Carapezza, Editor, Proceedings of SPIE Vol. 5090 (2003) © 2003 SPIE · 0277-786X/03/$15.00

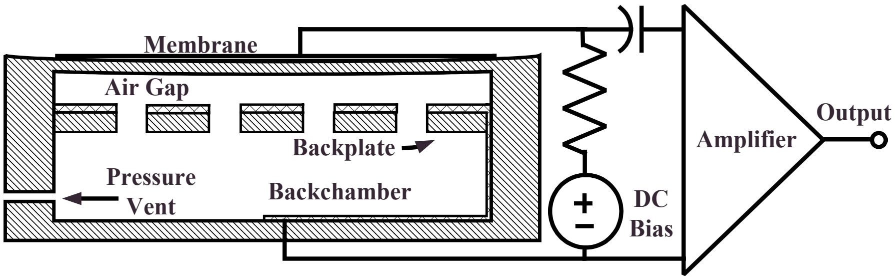

Figure 1. Schematic cross-sectional view of a condenser microphone.

In a micromachined microphone, the membrane is made as thin as possible to maximize the response of the membrane to sound. Sensitive electrical detection of the membrane movement is accomplished with a single large membrane and a narrow air gap, typically in the range of 1–2 μm.[1] While many such devices are sensitive, there are some disadvantages to this mechanical structure. Achieving large dynamic range and high sensitivity are usually conflicting goals, since high sound pressure levels may cause the membrane to collapse under its voltage bias.[5] In addition, the air gap and the acoustic holes in the backplate introduce frequency-dependent stiffness and loss, often dominating the stiffness of the membrane and causing variations in the mechanical response with frequency.[6] Furthermore, the bandwidth of these microphones is limited at low frequencies since the transducer capacitance and input resistance of the amplifier form a high-pass filter that attenuates low frequencies. There also is a low-frequency mechanical roll-off in the membrane response due to the pressure equalization vent in the microphone backchamber.[7] Finally, miniature condenser microphones can be susceptible to condensation in the narrow air gaps when exposed to moist environments or sudden temperature changes.[2] Moisture in the air gap can hinder membrane movement and may require regular cleaning to remove.

2.2. A Sealed Membrane Structure

An alternative approach to capacitive sensing uses many smaller membranes, such as capacitive micromachined ultrasonic transducers (CMUTs), which have been developed for generation and reception of ultrasound in air and water.[8, 9] A single CMUT membrane's structure, shown in Fig. 2, is similar to that of a conventional condenser microphone membrane, but differs in dimensions and thus range of applications. The membrane, which can be circular or rectangular, is surface-micromachined silicon-nitride suspended suspended over a silicon substrate. The top surface of the membrane is metalized to form one electrode, while heavily doped polysilicon forms a second electrode for the capacitor. A typical membrane for applications in air has a diameter or length of 70–100 μm, a thickness in the range of 0.5–1 μm, and a measured tensile stress of about 120 MPa.[10] The above device geometry results in a structure that resonates at several megahertz, and is therefore typically used for ultrasound applications in air or immersed in water.

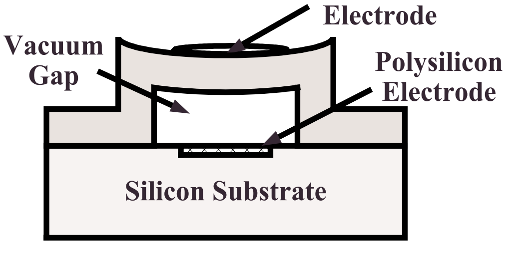

Figure 2. Structure of a single CMUT membrane.

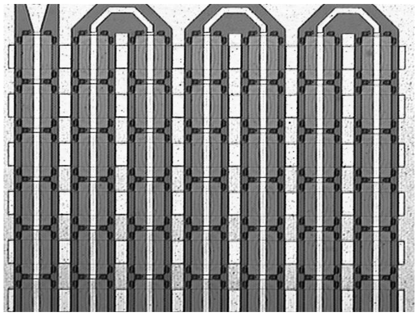

Figure 3. Photograph of a portion of a 1 mm^2 microphone formed by covering an array of 90-μm by 135-μm rectangular CMUT membranes with a transmission line.

This structure can be used as the basis for a microphone for sensing frequencies in the ultrasonic, audio, and infrasound ranges. With smaller membranes, the volume beneath the membranes may be evacuated during fabrication, and the membrane will still withstand atmospheric pressure, or higher, without collapsing to the substrate. This sealed membrane structure has many important implications for microphone performance. First, the absence of air or a perforated backplate completely eliminates the squeeze-film damping effects. The energy loss due to squeeze-film damping is the dominant source of noise in many condenser microphones.[11, 12] In addition, the frequency-dependent compliance due to damping is eliminated, resulting in less variation of the membrane response to pressures of different frequencies. Because the volume behind the membrane is sealed, the membrane also responds to arbitrarily low frequencies, including atmospheric pressure fluctuations, provided the electronic detection system is designed to detect these. Unlike standard condenser microphones, which have pressure equalization vents, there is no acoustic roll-off at low frequencies associated with the mechanical structure. Because CMUT membranes resonate at a few megahertz, the displacement response of such membranes to pressure inputs is constant up to several hundred kilohertz, resulting in a very wideband sensor. As with all microphones, diffraction effects and packaging design must be considered as the size of the microphone becomes comparable to the wavelength of sound at high acoustic frequencies.

3. RADIO FREQUENCY DETECTION WITH CMUT MEMBRANES

The major tradeoff of smaller membranes is a reduction in membrane displacement for a given input pressure. To obtain a sensitive microphone, this reduction in displacement response must be compensated for with an extremely sensitive method of detecting slight changes in capacitance, without significant degradation of the signal-to-noise ratio. Radio frequency (RF) detection is an alternative method to constant-voltage bias for sensing the slight changes in capacitance due to membrane movement.

3.1. Microphone Description

In RF detection, the microphone is formed by snaking a coplanar waveguide transmission line to cover an array of tens or hundreds of CMUT membranes, as shown in Fig. 3. The membranes are fabricated on high-resistivity silicon to reduce substrate loss due to induced eddy currents from the RF signal.[13] Schematically, the metalized CMUTs and the doped polysilicon electrodes underneath the membranes form variable capacitors, spaced at regular intervals along the transmission line as shown in Fig. 4. As the capacitive membranes in the line vibrate due to incoming sound pressure, the propagation constant of the transmission line also changes, effectively modulating the electrical length of the line. If a radio frequency carrier signal is launched down the membrane-loaded transmission line, it is phase-modulated by the acoustic signal. These phase changes in the RF signal can be detected, or demodulated, to recover the acoustic signal.

A lumped-element approximation for phase length of the loaded transmission line in radians is given by the expression[14, 15]

$$\Phi = N\omega_{RF}\sqrt{L_t d(C_t d + C_{mem})}, \tag{1}$$

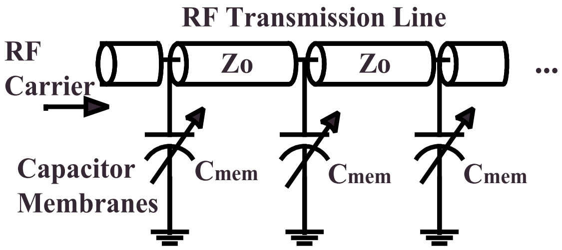

Figure 4. Structure of a periodically-loaded RF transmission line, with CMUT membranes forming variable capacitors along the line.

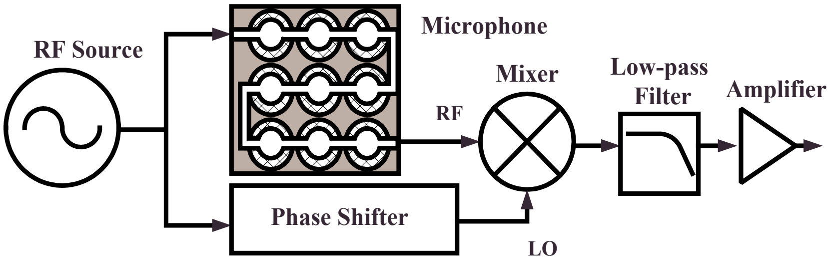

Figure 5. Block diagram showing the microphone as part of a phase detection circuit to recover the incident acoustic signal.

where N is the number of membranes or sections, ω_{RF} is the radian frequency of the RF carrier signal, L_t and C_t are the inductance and capacitance per unit length of the transmission line, C_{mem} is the membrane capacitance, and d is the periodic spacing between capacitor membranes. This expression illustrates how the membrane capacitance is incorporated into the transmission line, and how propagation (in this case, the phase length of the line) is modified by changes in C_{mem}.

3.2. Detection Electronics

Changes in Φ can be sensed when the microphone is included as part of a phase detection circuit, such as the one shown in Fig. 5. This circuit is commonly used in phase noise measurement systems to detect phase fluctuations in electrical devices.[16] In this circuit, an RF signal source is split into two branches. One branch passes through the microphone, which phase modulates the RF signal by the acoustic pressure on the CMUT membranes. The second branch forms a reference signal which is mixed with the modulated signal from the microphone. If the reference signal and microphone signals at the mixer are in quadrature, the phase variations in the microphone branch are detected and subsequently amplified.

A simple approximation for the signal output of the mixer demonstrates the sensitivity of the method. Differentiating the expression for Φ in Eq. (1) with respect to C_{mem} and linearizing the expression for small changes in C_{mem} yields

$$\Delta\Phi \approx \frac{N\omega_{RF}\sqrt{L_t}}{2\sqrt{C_t}}\Delta C_{mem} \ . \tag{2}$$

The expression can be written in terms of the characteristic impedance of the unloaded transmission line, given by $Z_0 = \sqrt{L_t/C_t}$, and small changes in capacitor plate separation x by linearizing the change in capacitance using, $\Delta C_{mem} \approx C_{mem}\Delta x/x$. Therefore, the total phase shift of the line is approximated by

$$\Delta\Phi \approx \frac{1}{2}N\omega_{RF}Z_0 C_{mem}\frac{\Delta x}{x} \ . \tag{3}$$

Equation (3) highlights some simple properties of this detection method. First, the amount of phase shift is proportional to the RF frequency ω_{RF} of the carrier, which may be several GHz or more. Clearly, higher RF frequencies will boost the electrical sensitivity until transmission line loss, which also increases with frequency, affects the system's ability to detect the phase changes. Secondly, there is no dependence on acoustic frequency as long as the membrane displacement Δx from its static position is invariant with acoustic frequency, which is the case for CMUTs operating below several hundred kilohertz. Thus, RF detection on vacuum-sealed devices permits sensing of arbitrarily low-frequency pressure fluctuations, within the limits of noise.

4. SIGNAL-TO-NOISE RATIO AS A MEASURE OF SENSITIVITY

Microphone sensitivity is traditionally described in terms of the output voltage response for an incident pressure. While this measure is useful for describing a condenser cartridge with or without a preamplifier, it is not obvious how it applies to RF detection, in which the performance of the transducer and detection circuitry are more intimately linked. Furthermore, since the use of volts per pascal neglects noise performance, it does not provide any information about the minimum detectable sound pressure of the sensor.

A more complete measure of sensitivity should incorporate both electrical and mechanical sources of noise. In this paper we commonly use signal-to-noise ratio (SNR), quoted in dB as a measure of microphone sensitivity. This ratio compares the signal level to the noise level after the first stage of amplification, for a given noise bandwidth and incident pressure. For the purposes of this paper, a 1-Hz noise bandwidth is selected to illustrate the spectral shape of the noise with audio frequency. As an example, an SNR measurement of 94 dB/Pa corresponds to a minimum detectable rms sound pressure of 20 μPa, or 0 dB sound pressure level (SPL). For simple comparison with other published sensitivities for microphones, the SNR also can be expressed as an A-weighted equivalent noise level by weighting and referring all of the noise sources to an equivalent pressure input.

4.1. Signal Levels

There are several stages to calculating the output signal and noise levels for a CMUT microphone with RF detection. First, the static dc deflection of the membrane under atmospheric pressure is either measured with an optical interferometer or calculated using a finite-element model or by solving the equations for a stretched diaphragm with bending stiffness and tensile stress.[17] Since the microphone operates below the membrane resonance, the same dc analysis also accurately describes the membrane motion for other frequencies of interest. The capacitance C_{mem} and change in capacitance ΔC_{mem} due to a single membrane cell is calculated for the electrode and signal metal dimensions, accounting for the deflection of the membrane due to atmospheric pressure. The resulting phase shift is given by Eq. (3).

The specific components of the detection circuit shown in Fig. 5 determine the conversion of phase shift $\Delta\Phi$ to output voltage. The phase detection constant K_D of the mixer in volts per radian can be measured directly in the circuit since it depends on the conversion loss of the mixer and the signal power at the mixer inputs.[16] Due to the dependence of the detection constant on RF power, the transmission line loss directly decreases the output signal level, almost dB-for-dB. Attenuation of coplanar transmission lines can be calculated[18] and the loading capacitances of the membranes can be included with slight modifications.[15]

4.2. Noise Levels

4.2.1. Mechanical Noise

The mechanical noise of a condenser microphone can limit the performance of the sensor, regardless of the quality of the amplifying electronics. Squeeze-film damping due to airflow through the backplate behind the membrane in unsealed membrane devices is the dominant mechanical noise mechanism for microphone cartridges. This noise is often referred to as self-noise, since it is a property of the microphone itself and its associated mechanical noise floor. The equivalent rms pressure noise per $\sqrt{\text{Hz}}$ is given by[11]

$$p_{rms} = \sqrt{4k_B T_0 R_{acs}}\ , \tag{4}$$

where k_B is Boltzmann's constant (1.38 x 10^{-23} J/K), T_0 is the absolute temperature of the system, and R_{acs} is the acoustic resistance representing all of the loss mechanisms of the membranes. By eliminating the major source of acoustical resistance, vacuum-sealed CMUT membranes have a much lower mechanical noise floor. The most significant noise source remaining is due to the radiation resistance of membranes, which exists for all acoustic sensors exposed to the air. As an example, one can examine the worst-case, upper bound for mechanical noise by substituting the plane-wave impedance of air scaled by transducer area to obtain R_{acs}. Therefore, a vacuum-sealed membrane area of 1 mm^2 has at most an equivalent rms pressure noise of 2.6 μPa in a 1-Hz bandwidth, and the noise is much smaller for frequencies in which the wavelength of sound is smaller than the transducer. Thus, mechanical thermal noise is negligible in most analyses involving sealed CMUT membranes. Instead electrical noise plays a more important role in limiting device performance.

4.2.2. Electrical Noise

There are several sources of electrical noise in the system. First, there is the thermal noise power on the microphone transmission line, given by k_BT_0 in 1 Hz. This noise is independent of the loss of the line as long as the system is in thermal equilibrium.[19] The quadrature component of this thermal noise is detected by the mixer, and again has value k_BT_0 in a 1 Hz bandwidth.[20] Furthermore, the mixer introduces its own noise, which increases roughly inversely with frequency at low-frequencies, known commonly as 1/f noise.[21] Subsequent amplification of the baseband signal also introduces additional thermal and 1/f noise into the system, though the overall noise floor of the system is usually determined by other components such as the mixer.

5. EXPERIMENTAL RESULTS

A 1 mm^2 area microphone consisting of 45 rectangular 70-μm by 190-μm membranes is connected as part of the phase detection circuit shown in Fig. 5. The remainder of the circuit consists of a 2.8 GHz dielectric-resonator oscillator signal source with output power of 20 dBm, a Minicircuits ZAPD-4 power splitter, a Marki Microwave M1-0204NA mixer, and a dc-coupled amplifier with 60 dB of gain constructed using the AD797 operational amplifier. The signal and noise levels are measured at the amplifier output using an SRS760 FFT spectrum analyzer.

5.1. Measurements

Measurements of amplifier output noise with a 50 Ω input termination indicate that its noise floor is well-below that of the mixer and can be neglected. Figure 6 shows the measured rms noise voltage in a 1-Hz band at selected points between 1 Hz and 100 kHz. The predicted curve is generated by assuming a typical 1/f corner frequency of 150 kHz for the mixer.[22] This noise floor is primarily a function of the circuit components and does not vary significantly with other microphone devices.

The sensitivity of the microphone in free-field conditions at normal incidence is measured using a speaker and sound meter. The volume of the incident sound at 1 kHz is adjusted to 1 Pa rms at the location of the microphone. A measured output voltage of -40.7 dBV rms yields an SNR of 65 dB/Pa at 1 kHz in a 1-Hz noise bandwidth. This sensitivity improves to 73 dB/Pa above 10 kHz. The sensitivity measurement agrees quite closely with predictions: with a calculated phase shift along the microphone's transmission line of 22 μrad, and a measured mixer phase detection constant of 0.38 V/rad for this microphone, the expected signal output after 60 dB of amplification is -41.7 dBV rms. The microphone sensitivity corresponds to an A-weighted, equivalent noise level of 59 dBA SPL, found by integrating and weighting the noise level over the audio band and referring the noise to the microphone input as a pressure.

Acoustic testing over many decades of frequency requires elaborate test equipment and special sound sources for generating extremely low frequencies. Our alternative method of testing the system's frequency response is to use electrostatic actuation of the CMUT membranes at infrasonic and ultrasonic frequencies. This is accomplished by inserting bias-T's before and after the microphone in the circuit in Fig. 5. The amplifier output is measured as the sinusoidal voltage actuation varies from 0.1 Hz to 100 kHz. Actuation at 1 kHz permits scaling of the output response for a sound pressure level of 1 Pa. The measured frequency response is also plotted in Fig. 6 and demonstrates that the membrane and detection circuit response varies less than 3 dB over six decades of frequency. Most of this variation is due to the amplifier frequency response and bias-T filtering effects. The predicted signal output level is also shown in Fig. 6.

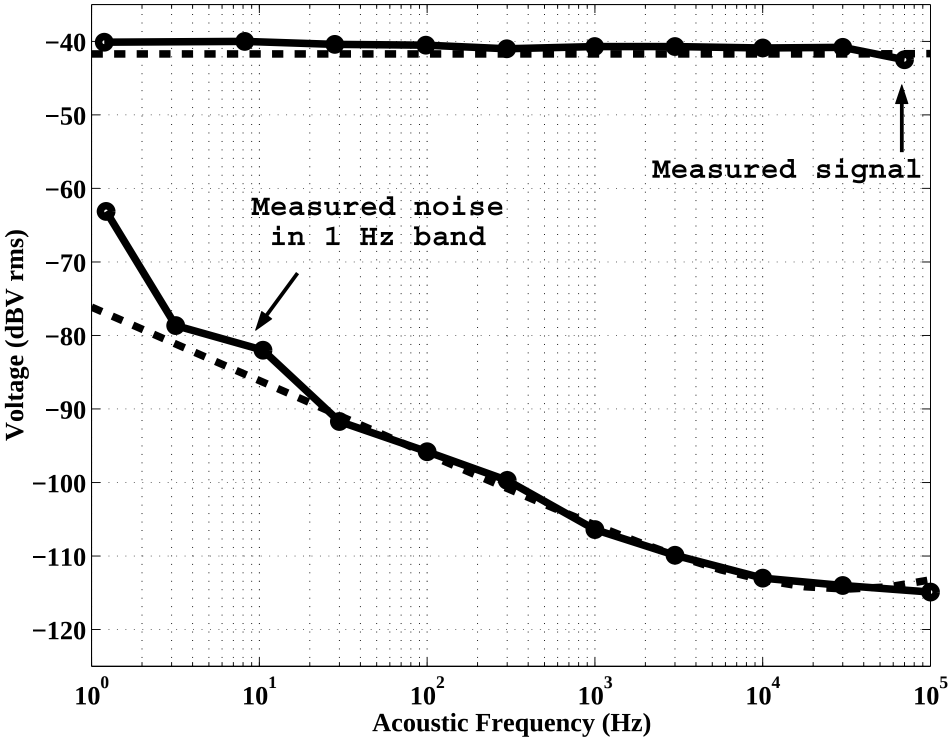

Figure 6. Measured (solid lines) and predicted (dashed lines) output signal and noise levels in dB relative to 1 V rms as a function of frequency. The noise levels are measured in a 1-Hz noise band and the signal levels are for a 1-Pa sound pressure.

5.2. Discussion

These microphone measurements demonstrate the flat frequency response of the microphone. Theory suggests that the response remains flat even below 0.1 Hz and above 100 kHz, though measurement equipment range limitations prevent confirmation. The sensitivity of the microphone can be further improved by increasing the degree of phase shift and lowering the electrical noise floor of the supporting electronics. Fabrication of larger CMUT membranes also increases individual membrane movement, while longer chains of membranes can further increase the phase shift of the line. Both of these result in an increase in area, which can be tolerated in most applications.

Further improvements in sensitivity are possible with other phase detection circuit topologies. Various carrier-suppression, or interferometric, phase detection techniques permit low-noise RF amplification prior to mixing, permitting 20-40 dB improvements in the noise figure of a phase measurement system.[23, 24] These topologies, though complicated to construct, could be particularly useful at low frequencies, since the effects of the mixer's 1/f noise would be mitigated.

6. CONCLUSION

The RF detection method discussed in this paper is a very sensitive method for detecting displacement. When combined with sealed CMUT membranes, a robust, waterproof microphone with very broad, yet flat, frequency response is possible. Experimental results using voltage actuation of the membranes demonstrate a relatively flat membrane response over six decades of frequency. The microphone noise level does increase at lower frequencies due to mixer 1/f noise. The measured sensitivity of a 1-mm^2 area device using CMUT membranes with RF detection is 65 dB/Pa at 1 kHz, increasing to over 73 dB/Pa for frequencies above 10 kHz in a 1-Hz band.

Considerable improvement in sensitivity is possible by using larger devices and more elaborate phase detection circuits. Most importantly, the sealed-membrane design of the microphone is completely weatherproof, capable of withstanding dusty, dirty, and moist environments.

ACKNOWLEDGMENTS

This work is supported by the Defense Advanced Research Projects Agency's Microsystems Technology Office. The devices were fabricated at the Stanford Nanofabrication Facility, which is supported in part by the National Science Foundation.

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