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#1

Dynamic Pressure Measurements

Final Report

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Research Objective:

The major objective of this project is to design, develop and build a high pressure (static and dynamic) and high-temperature testing facility to calibrate the performance of acoustic sensors for condition monitoring of gas turbine engine components. This dynamic pressure testing facility will then be used to develop a benchmark calibration procedure for acoustic sensors and to develop transfer functions to characterize the effect of sensor mounts. A graduate research assistant will be exclusively devoted to these high pressure calibration methods, particularly to the calibration of a variety of sensor configurations. This work will develop a systematic calibration procedure that identifies sources of noise (and their elimination) and improved data acquisition, including signal processing. The final portion of this project will complete optimization and characterization of the high temperature version of our MEMS sensor. This includes process development, implementation, sensitivity testing, and survivability/production issues.

Benefits to GEPS:

A dynamic pressure testing facility is being used to develop a benchmark calibration procedure for acoustic sensors and to characterize the effect of sensor performance and mounting. The MEMS acoustic sensor enables robust, in situ acoustic measurements through higher temperatures and a broader frequency bandwidth than currently possible.

High Temperature MEMS Sensor Development and Testing:

The schematic of the acoustic MEMS sensor developed in this project is shown schematically in Fig. 1. It consists of a surface micromachined reflecting membrane and a diffraction grating built on an optically transparent substrate. The gap between the membrane and the grating is vacuum-sealed so that any external pressure will deflect the membrane. This deflection is measured by illuminating the diffraction grating from the backside through the transparent substrate, and monitoring the intensity of the reflected diffraction orders.

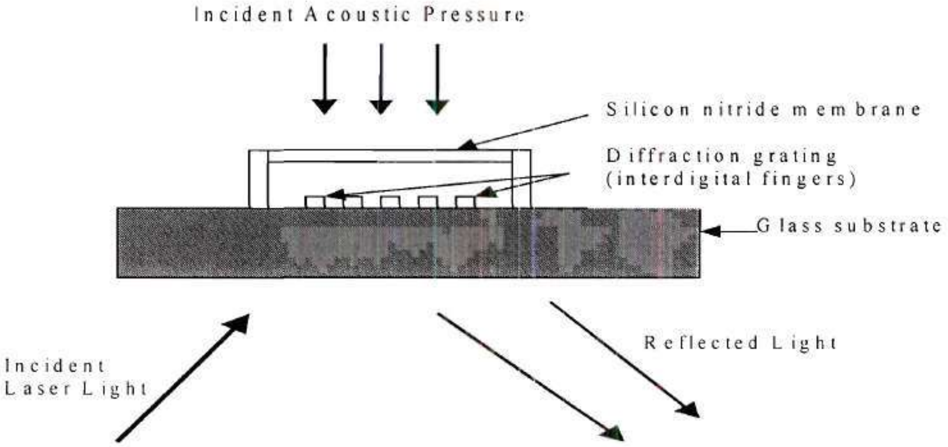


Figure 1. Schematic of the MEMS acoustic pressure sensor based on phase sensitive optical diffraction grating.

A low temperature version of the MEMS sensor has already been fabricated on quartz substrate using aluminum as the material for the diffraction fingers and the sensor membrane in the first part of this project. One of the aims of the current project was the development and testing of an acoustic MEMS sensor that can operate at high temperatures.

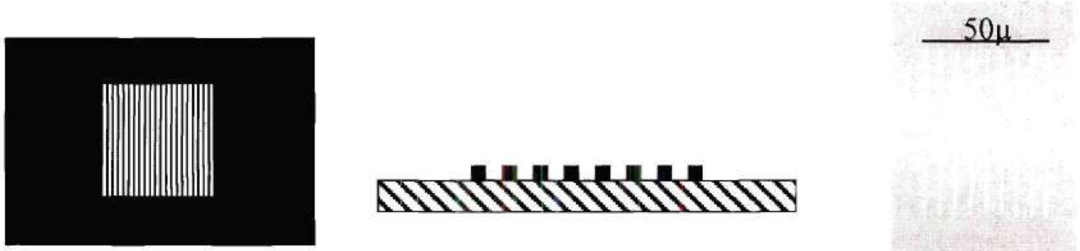
Fabrication of High Temperature Sensor

The fabrication of the high temperature sensor was done using traditional microelectronic fabrication techniques. To produce a high-temperature sensor, high-temperature materials are needed. The choices for these materials include: sapphire for the substrate, polysilicon for the diffraction fingers, and silicon nitride for the sensor membrane. Because of the high cost of sapphire wafers characterization of the fabrication steps was done on silicon. In the following, the steps involved in the fabrication of the high temperature acoustic MEMS sensor are described in detail.

Diffraction Grating

The first step in the fabrication process was the deposition of polysilicon. This deposition was done in an LPCVD (low pressure chemical vapor deposition) furnace. Before placing a wafer into the LPCVD furnace, it has to be subjected to a thorough cleaning procedure. The procedure includes rinsing the wafer with Acetone and Methanol and submersing the wafer in sulfuric acid and hydrogen peroxide. A 40 min. deposition at 588°C was done in the LPCVD furnace to deposit a polysilicon layer of 2400Å on both sides of the sapphire substrate.

The next step in the process was to pattern the diffraction grating. To create the diffraction grating, a photoresist layer must be spun and patterned. Shipley 1813 was the photoresist of choice. To create a 1.5μm layer of resist, the wafer was spun at 3000 rpm. Using standard photolithography, the resist was patterned and developed. To etch the polysilicon, the ICP (Inductively Coupled Plasma) System was used. Utilizing a 10 second etch step and SF_6 as the etching gas, the polysilicon was removed. The remaining photoresist was then stripped from the wafer leaving the diffraction fingers on the substrate. Figure 2 shows the photolithographic mask, the crosssection of the wafer at this stage and also the top view of the patterned polysilicon layer.



Mask Cross Section Diagram Top view

Figure 2. The mask and the top view of finished polysilicon finger layer on sapphire wafer.

Sacrificial Layer

To create the cavity between the sensor membrane and the diffraction finger layer, a sacrificial layer of PECVD (plasma enhanced chemical vapor deposition) silicon oxide was deposited onto the front of the wafer. This was performed using a STS PECVD system. The target thickness of the silicon oxide layer was 1.5µm. A 40:30min. deposition run resulted in a 1.5-1.6µm deposition on the silicon wafer and a 1.3µm layer on sapphire.

The sacrificial layer was then patterned using a photoresist mask layer. For this application, Shipley 1827 is used as the masking layer. When spun at 3000 rpm, 1827 produced a thickness of ~3µm. A thicker resist was needed because the etching process used for silicon oxide has poor selectivity to the masking layer. Using the ICP, the silicon oxide layer was etched down to the sapphire wafer surface by etching for 7:30min. The photoresist was then stripped leaving the sacrificial oxide. The recipe used for silicon oxide resulted in sloped edges on the sacrificial layer than vertical sidewalls. This shows that the etching was more chemical than mechanical, and therefore resulted in an isotropic etch. These sloped edges can be seen in the images from the membrane release section below. Since the membrane is deposited over this layer, it shapes the membrane. Figure 3 shows the sacrificial layer mask as well as the picture of the top view of the patterned layer. Also patterned at this stage is the etch channels for subsequent sacrificial layer etching. These are seen as the thin lines with a square shape at four corners of the circular membrane.

Mask Cross Section Diagram Top view

Figure 3. The mask, cross sectional diagram of the wafer and the top view of patterned sacrificial layer.

Sensor Membrane Fabrication and Etch hole patterning

The sensor membrane is the most critical part of the design. The membrane is formed using LPCVD silicon nitride. According to earlier design studies, a 1µm thick membrane is desired for a 50µm diameter. A deposition of silicon nitride for 7 hours at 800ºC produces a 0.95-1µm thick film. Also note that since the deposition was done in a LPCVD furnace, the nitride film was deposited on both sides of the wafer. Figure 4 shows the cross-section of the sensor after membrane deposition. No mask is required for this processing step and the top view is identical to that shown in Figure 3.

In order to release the membrane, holes must be drilled into the etch channel region of the silicon membrane so that the sacrificial oxide can be removed. To pattern these holes, Shipley 1827 was used. Similar to the oxide process, etching of nitride in the ICP results in poor selectivity to the masking photoresist. After patterning and developing the etch holes, the sample was etched in the ICP for 6:10 min. This etch time was sufficient to etch through the nitride exposing the oxide. The etch hole mask, the cross sectional diagram and the top view of the membrane after this step are shown in Figure 5.

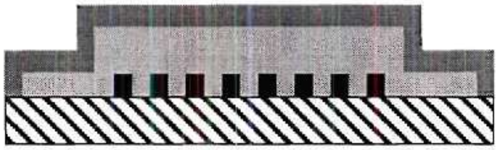
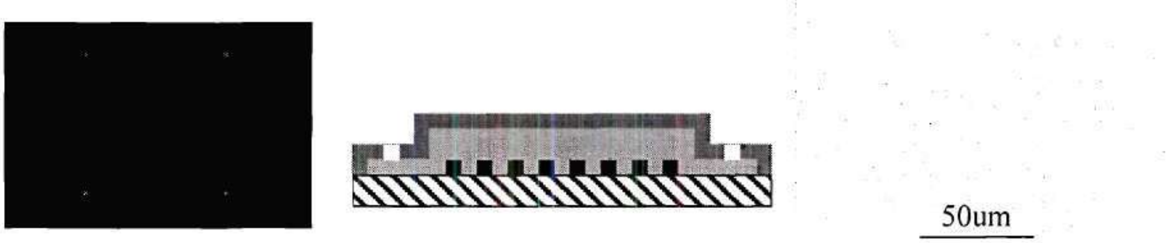


Figure 4. Cross sectional diagram of the wafer after membrane deposition.



Mask

Cross Section Diagram

Top view

Figure 5. The mask layer and the top view of a 40μm diameter membrane with etched holes.

Backside Etch

As shown in Figure 1, optical diffraction is the chosen detection method for this sensor. In order to get a signal from the membrane, the backside of the substrate needs to be transparent. The earlier LPCVD processes deposited nitride and polysilicon on the backside of the wafer. This hinders the transmission of light through the wafer. To ensure the strongest signal, these layers were removed using the ICP. A process time of 7:45 min. was used to etch through both layers.

Dicing

At this point the wafer was diced in to individual pieces, or dies. One of the advantages of MEMS processing is that one gets a large number of devices from a single wafer. In this particular case one wafer produced about 20 identical dies each having nearly 50 sensor membranes.

Membrane Release

To create a sensor membrane that is free to vibrate, the sacrificial silicon oxide layer must be removed. For this process the sample was placed in BOE (Buffered Oxide Etch). BOE contains HF (Hydrofluoric Acid), which is the optimum wet etchant for silicon oxide. The etch rate of BOE is typically on the order of 1000 Å/min. for thermal oxide. Because the sacrificial oxide layer was formed using PECVD and thus less dense, the etch rate was higher. Determining the etch rate was not simple because mass transport is limited by the small etch channels. As it turns out, 6 hours was adequate to release some of the smaller membranes (40, 50, 60μm diameter). Since HF etches silicon nitride with a much slower, but finite rate as compared to silicon oxide, the 6hour etch also etched 0.2μm of the nitride membrane. This results in a 0.8μm thick silicon nitride sensor membrane. Figure 6 shows instances from this process for some large membranes, which are not completely released.

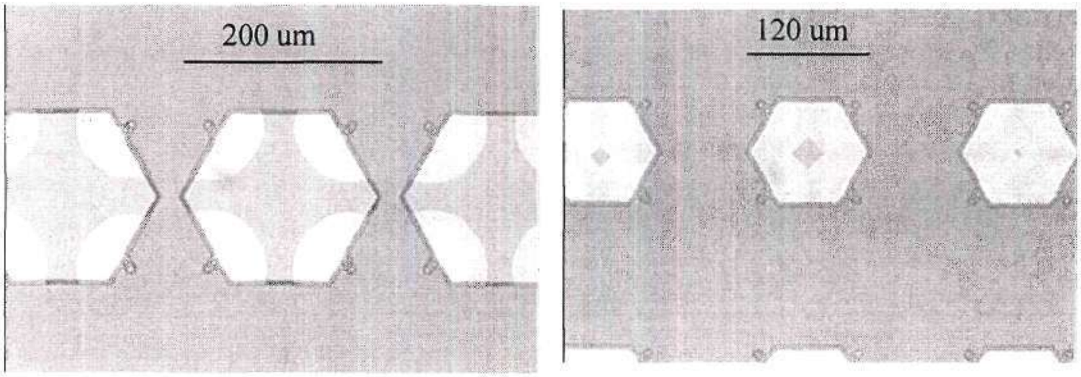


Figure 6. Top view of some large membranes during the membrane release process.

Fully released MEMS sensor membranes are shown in the SEM pictures in Figure 7. These membranes are 40μm in diameter and 0.8μm thickness resulting in ideal dimensions for the high temperature MEMS sensor. Also note the slight bowing of the membranes. This is due to the large mismatch between the thermal expansion coefficients of sapphire and the silicon nitride membrane material. The sapphire has a much larger CTE as compared to silicon nitride, causing the membrane be placed under compressive stress when the samples is brought down to room temperature after deposition at 800°C. This compressive stress is released by the bowing of the membrane when the sacrificial layer is etched away. This is an advantageous feature for high temperature operation, since the membrane will be flatter at high temperatures.

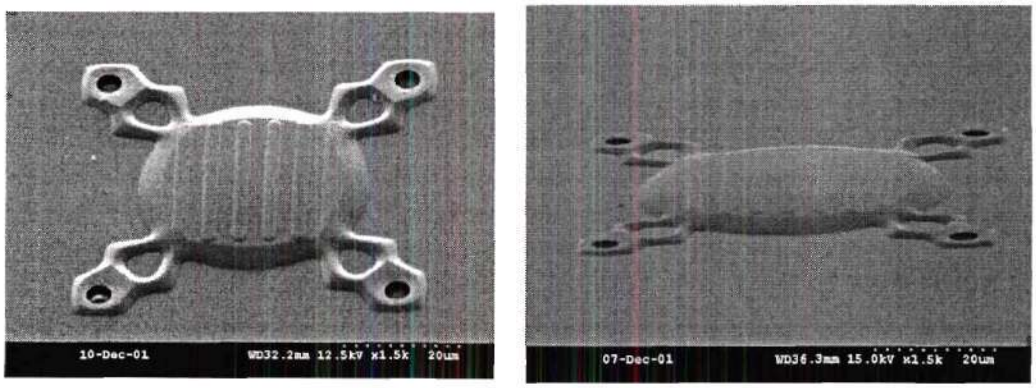


Figure 7. SEM pictures of successfully released membranes from two different angles. The impressions of diffraction fingers as well as the bowing of the membrane are visible in the images.

High Temperature Survivability Test

The MEMS sensors are subjected to high temperatures to find out if they remained intact and still functioned as acoustic sensors after thermal cycling. For this purpose, the sapphire wafer piece carrying MEMS sensor membranes is placed in a high temperature furnace and the temperature is raised to a target value, kept at the target value for 10min and then the sample is cooled down to room temperature and inspected under an optical microscope for damage such as cracks etc. During the tests the temperature levels of 152, 223, 323, 422, 505, and 600°C are used. The optical inspection showed no damage to the membrane. Furthermore, after the 600°C test the sample is imaged using the SEM to make sure that the membrane is inspected thoroughly for structural damage, since the SEM clearly shows any such problem. Figure 8 shows the MEMS sensor membrane after the thermal cycling. There are no cracks or other damage on the sensor membrane. Hence we conclude that the high temperature MEMS sensor can safely be used up to600°C.

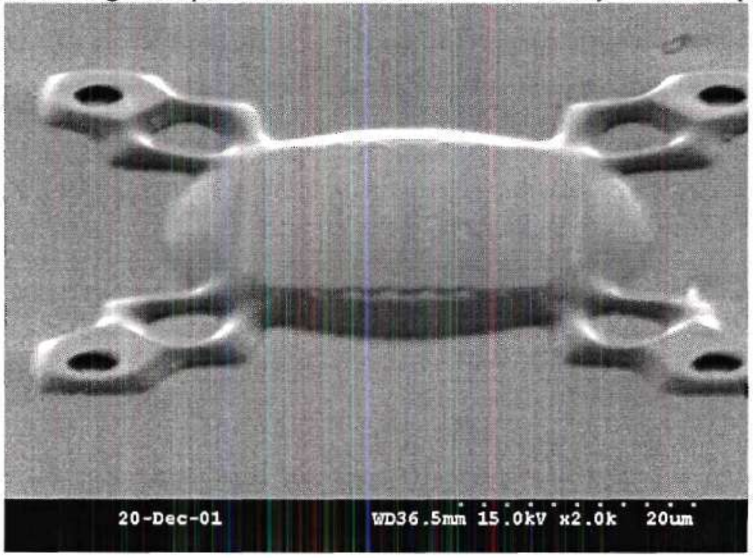


Figure 8. SEM pictures of MEMS sensor membrane after thermal cycling at 152, 223, 323, 422, 505, and 600°C. The membrane is 40μm in diameter and the thickness is 0.8 μm. No structural damage is observed. This membrane is also used for successful acoustic testing.

Acoustic Testing of the High Temperature MEMS Sensor

The setup shown in Figure 9 is used to measure the performance of the high temperature MEMS sensor for detecting acoustic waves. A HeNe laser is focused on one of the MEMS sensor membranes from the backside illuminating a diffraction grating. The acoustic waves are generated by a speaker located in the front of the sensor wafer. The first diffraction order intensity is detected using a photodetector.

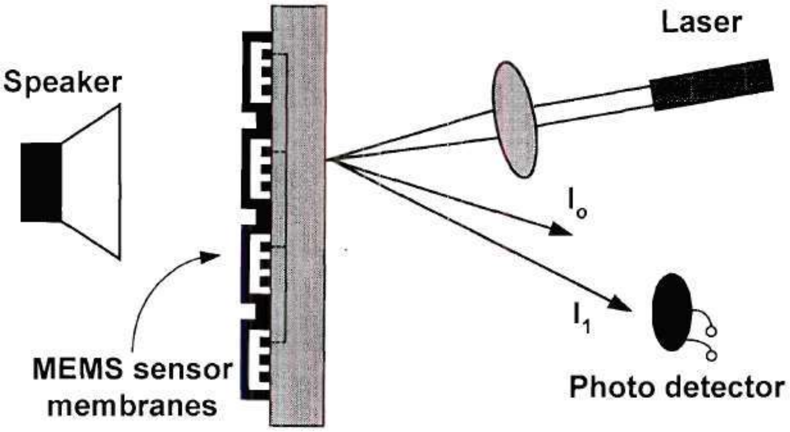


Figure 9. Schematic of the experimental setup used for acoustic testing of the MEMS sensor.

For acoustic testing, a 20kHz sinusoidal tone burst signal is applied to the speaker. The sound level of the generated signal at the MEMS sensor surface is measured using a calibrated acoustic receiver. The signal level was found to be in the 90dB to 94dB range corresponding to 0.6 to 1 Pa pressure levels. Figure 10 shows the signals received by the MEMS sensor after the thermal cycling for 5-cycle and 8-cycle tone burst excitation. Both the time delay from the excitation signal, and the length of the responses show that the acoustic signals propagate through air. Hence this proves that the MEMS sensor is capable of detecting pressure levels in the Pascal range. Also note that the distorted shape of the received signal is due to the non-ideal response of the speaker and reflections in the setup.

When the speaker-MEMS sensor is varied, it is observed that the time delay also changes. Figure 11 shows the received signals for distances of 2.5, 3.75 and 5 cm separation between the speaker and the sensor along with the excitation signal. The time delay between the input and output signals and the change in the delay time between different separations correspond to 330m/s, which is the speed of sound in air.

In conclusion, the MEMS sensor is successfully tested to be operational after temperature cycling at 600°C and it is shown to detect acoustic pressures in the Pa range. This sensor should be useful for applications at high temperatures with pressures ranging from Pa level to several Psi.

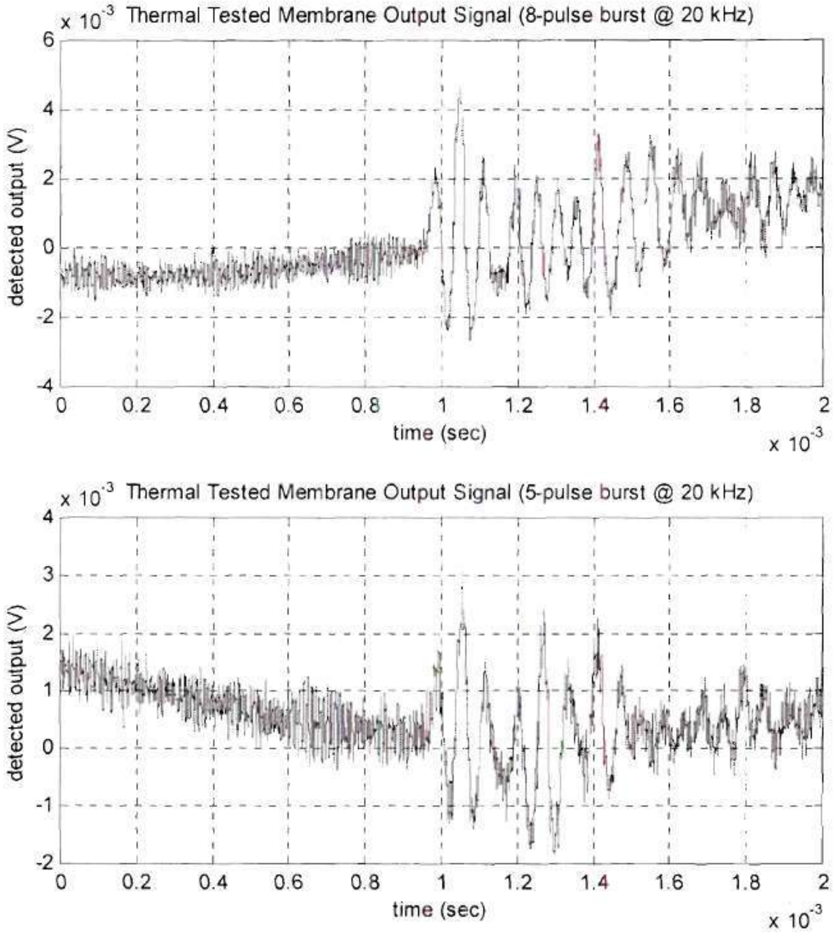


Figure 10. Received signals for 8-cycle (top) and 5-cycle sinusoidal input signal to the speaker placed 5cm away from the MEMS sensor.

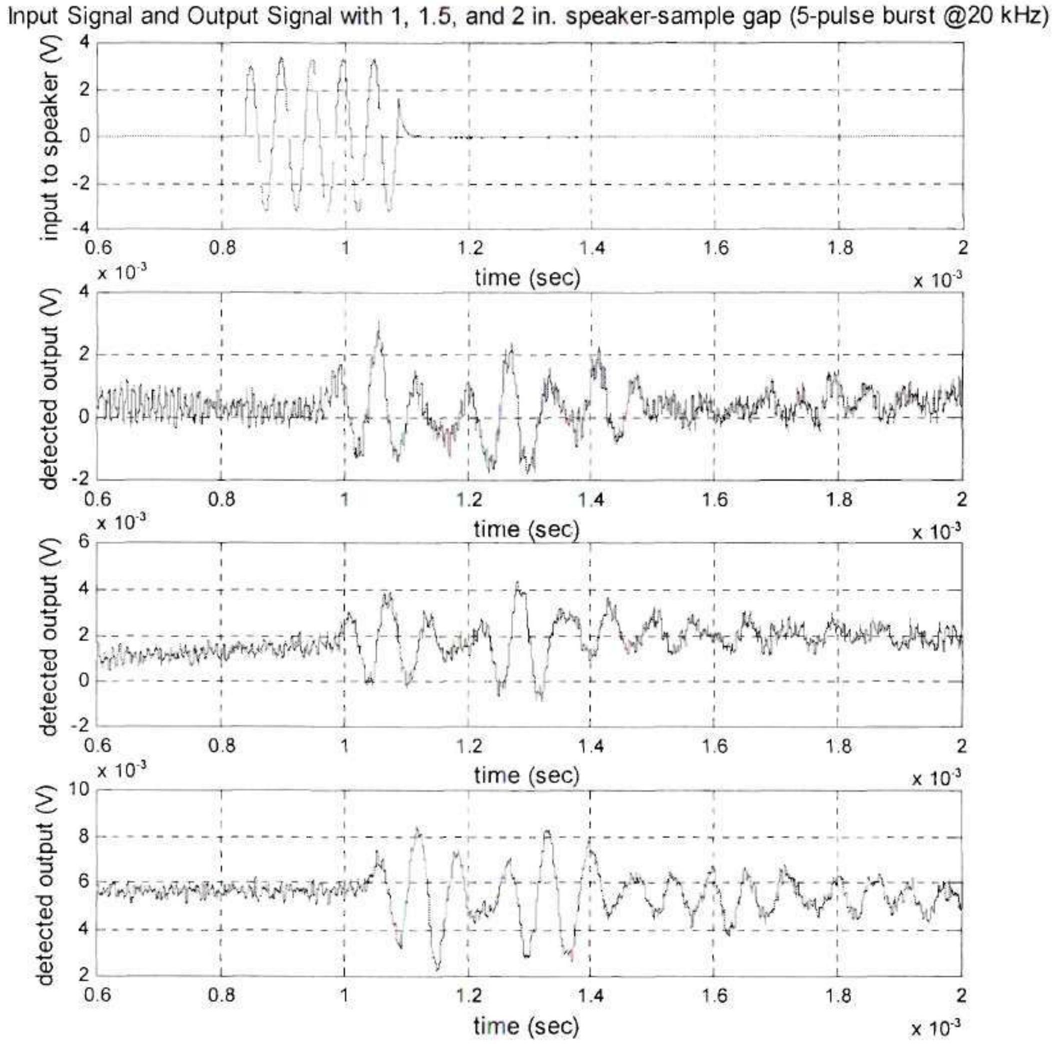


Figure 11. The input to the speaker (top) and received signals for speaker-MEMS sensor separation of 2.5, 3.75 and 5cm.