Surface Micro-Machined Capacitive Pressure Sensor

Scott Raguse

***Abstract*---This project entailed the design, fabrication, and testing of a surface micro-machined electret pressure sensor with the possible use as a microphone. The design is based on a capacitance electret microphone. This type of microphone uses a plate that has a built in charge to provide the bias of the system. This eliminates any external bias directly attached to the sensor. The surface micro-machining means that no backside etch is required to form the membrane. Without the backside etch the process can be integrated with a CMOS process much more easily. This electret pressure sensor uses a poly-silicon floating gate that has a fixed charge Q place on it to create an internal bias between the floating gate and the upper aluminum diaphragm. This means that the device can run without a sustained external bias, instead of the constant bias that a condenser pressure sensor/microphone requires. The devices were fabricated on 6 inch wafers, using a 2 metal and floating gate process. The testing showed that the control gate was shorted to the n-well. This meant the floating gate could not be charged, thus the device could not be tested properly. The process did show the viability of the surface processed diaphragms. They were completely released from the sacrificial resist, and were shown to hold their shape.**

***Index Terms*---CMOS compatible, electret, floating gate, surface micro-machined**

I. INTRODUCTION

THE MEMS industry is one of the fastest growing sectors of the semiconductor industry. To make the devices compatible with CMOS technology, the use of a backside etch to form a diaphragm needs to be discontinued. If a device can be created using only surface techniques, then the CMOS circuitry can be integrated on chip with the MEMS device. This saves cost and results in a smaller package. Small microphones are needed in many applications such as hearing aids, cell phones, and even in some car systems. MEMS microphones are ideal for these applications due to their low cost small package.

Electret microphones lend themselves for such MEMS manufacturing and small scale microphones. The microphone does not require an external bias. An amplification circuit does require power, but this would be required in a condenser microphone also.

II. THEORY

Capacitive Microphones

Capacitive microphones work on the concept of voltage changes from a variable capacitor. One of the plates of a capacitor is a diaphragm that is sensitive to sound pressure waves. The two plates are biased with a fixed charge Q. Since the capacitance equation states Q = CxV, and Q is held constant, that mean the voltage V must change when the capacitance C changes due to the diaphragm deflection [1]. This change in V is measured and the fluctuations are the electrical representation of the sound waves. In a condenser microphone Q is produced by a constant DC bias or from a RF voltage. An amplification circuit, which also has to be powered, is usually also required to produce a usable signal [2].

An electret microphone works on the same principle as a condenser microphone; however, in an electret microphone Q is built into the device. The term "electret" is used to describe a material that has been permanently electrically charged. Since the electret plate of capacitor already has a fixed charge Q, there is no need for and external bias for the device. Power is still needed to run the amplification circuitry that produces a useable electrical signal from the small voltage changes from the diaphragm deflections [1].

Diaphragm Calculations

The diaphragm for a pressure sensor or a microphone needs to be ridged enough to easily support itself, but also flexible enough react to desired pressure changes. Aluminum is a easy material to work with when performing MEMS surface processing. The thickness of the material and the capable size of a circular diaphragm can be calculated by using Equation 1.

$$y = \frac{3PR^4\left[(1/\nu)^2 - 1\right]}{16E(1/\nu)^2\delta^3}$$

Equation 1: Maximum deflection of a circular diaphragm

Where P is pressure, R is the radius, δ is the thickness, ν is Poisson's Ratio, and E is Young's Modulus. This equation give the maximum deflection at the center of the diaphragm at a given pressure [3].

III. PROCEDURE

Design

To form the electret pressure sensor a chargeable electret material needed to be chosen. A charging mechanism also needed to be determined. Poly-silicon was chosen to be the electret material. The poly-silicon would be isolated by SiO_2 and become a floating gate. The floating gate would then be charged using Fowler Nordheim tunneling through a thin gate oxide separating the poly-silicon from the silicon substrate. This would then require a control gate. The Al diaphragm was first considered for this task, but an air gap of 1μm, the desired separation, would be too great to produce tunneling. It was decided then to use a two metal process, in which metal 1 would be used as the control gate and metal 2 as the diaphragm.

The diaphragm was determined to require a 2μm thickness

in order to support itself. The ideal diameter of the device was then determined to be about 100µm. It was then determined to have diaphragms of 50, 100, 150, and 200µm in diameter. This would provide different sensitivities, and provide some data on the durability of the Al diaphragms. Fig. 1 shows design of the sensor. The dimensions were then just scaled for the other sizes.

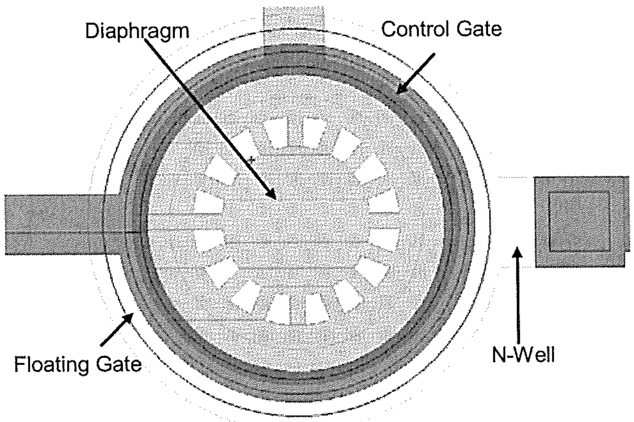

Fig. 1: Device layout

Process

For these devices it was decided to use 6 inch wafer and the corresponding toolset. The starting substrates were 10Ω-cm P-type wafers. A 500Å pad oxide was then thermally grown on the substrate. Next 1500Å of nitride was deposited using LPCVD process. This would be used to for a LOCOS process in order to produce alignment marks on the wafer. Photo 1 was then performed on the Cannon i-line stepper to defined the N-well regions and the alignment marks. A dry etch was used next to remove the nitride from the exposed areas. The wafers were then ion implanted with P31 at a dose of $2x10^{15}$. The photo resist was then removed and an RCA clean was performed on the wafers. The wafers were then placed in the furnace to grow a 4000Å wet oxide. The nitride and oxide were then removed using wet chemistry. In order to provide a uniform gate oxide growth, a 1000Å Kooi oxide was grown next. This was stripped and a 150Å dry gate oxide was grown on the wafers. LPCVD poly-silicon was then deposited to a thickness of 5000Å. The poly was then doped using an ion implant of P31 at 60keV at $4x10^{15}$ to form an N+ poly floating gate. During the furnace activation, a 500Å oxide was grown on top of the poly to form the control gate oxide. To protect this oxide, a 1500Å LPCVD nitride was deposited.

Photo 2 was next defining the floating gates. Dry etch was then used to etch through the entire gate stack. Once the resist was removed and the wafers cleaned, a 3000Å SiO_2 was deposited using a PECVD TEOS process. Photo 3 then defined the contact cuts and the control gate opening. The oxide was etched in BOE. The exposed nitride layer protecting the control gate oxide was then etched away using a hot phosphoric etch. This provided a very good selectivity between the nitride and the SiO_2. A 5000Å Al layer was then deposited using the CVC 601 Sputter. Photo 4 then defined the metal 1, which was etch using the wet Al etch. Another 3000Å ILD was deposited and photo 5 was performed to define the via's and also to open up the region that will be the air gap under the diaphragm. The oxide was etched away using a BOE bath. Photo 6 was then performed to apply a 1µm photo resist layer that would act as the sacrificial layer to form the air gap under the metal 2 diaphragm. The 2µm metal 2 was then deposited using the CVC 601. Photo 7 then defined metal 2 and the Al etch bath was used to remove the unprotected Al. An O_2 plasma ash was then used to remove both the metal 2 definition resist, and the underlying sacrificial resist. The plasma had access to this resist through opening in the metal 2 layer. Fig. 2 shows a cross-section of the completed process, and Fig. 3 shows a top down view of a fully processed device.

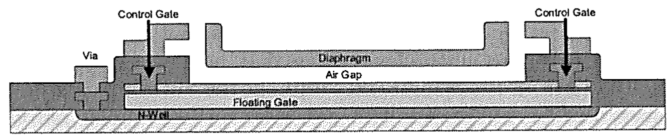

Fig 2: Device cross-section

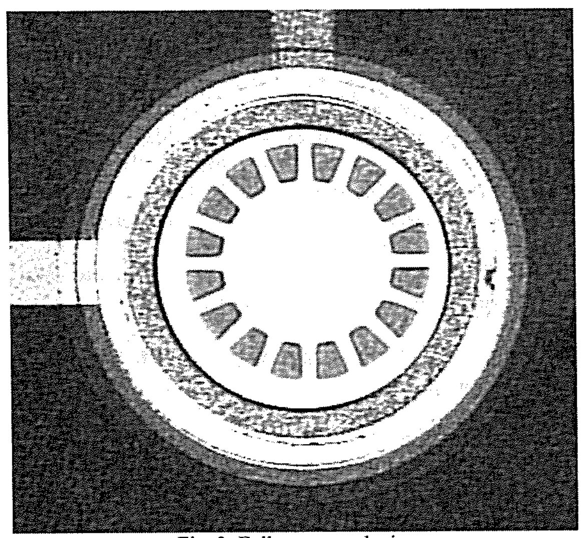

Fig. 3: Fully process device

IV. RESULTS AND DISCUSSION

Testing

The devices were initially tested using a probe station to characterize the tunneling and view any changes in the voltage drop across the N-well and the diaphragm. It was determined at this point that the control gate was shorted to the N-well. This meant that the floating gate could not be charged. In order for the device to work the floating gate needs to have a fixed charge Q placed on it. Since the floating gate was designed to be isolated there was also no chance of testing the diaphragm as a condenser microphone. All three of the fully processed wafers were found to have this same short.

The cause of the short is believed to be a combination of factors. The floating gate dry etch etched to far and went into the substrate. This caused the exposed surface to become rough and pitted. This pitting was translated into the ILD layer. This could have cause some unexpected etching during the contact etch, thus opening a path for the control gate to short to the substrate or the floating gate.

Diaphragm Integrity

The diaphragms were found to hold up and keep their shape very well. There were some issues with the diaphragms lifting off. This most likely happened in the spin rinse dryer after the Al etch. The edge of the sacrificial resist provided a stress point for the metal to break off. Once the structure was weekend my etching away some of the metal, the stress of the water jets and spinning could have proved too much for some of the diaphragms to handle.

Fig. 4-6 show images of the finished devices taken using the Veeko Wyko profiler. This tool uses white light interferometry to map surface heights and produce a 3D image of water structures. The images show the diaphragms to be very flat. In fact these two devices showed only on 500nm variance in height across the entire 150μm diaphragm.

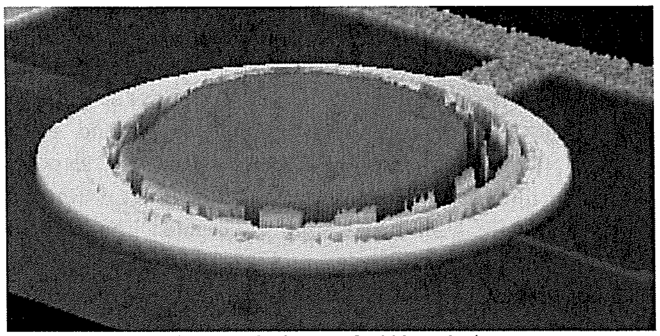

Fig. 4: Wyko image of a 200μm device

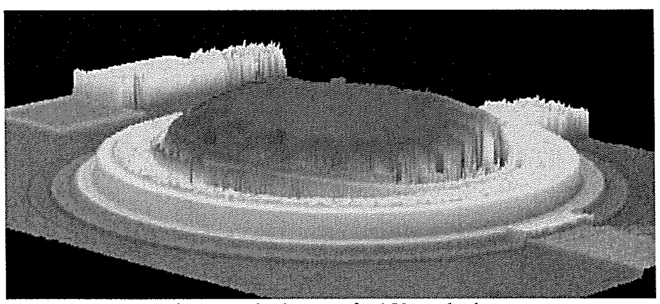

Fig. 5: Wyko image of a 150μm device

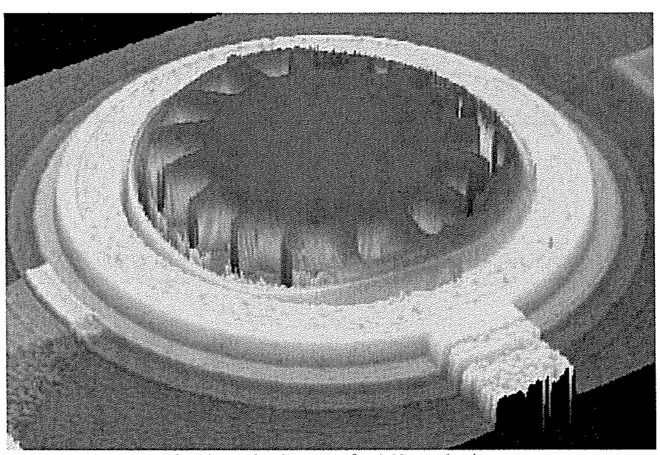

Fig. 6: Wyko image of a 150μm device.

By imaging one of the devices that lost the diaphragm, Fig. 7, a profile of the air gap could be taken. This profile shows that from the remaining metal 2 layer down to the nitride layer above the floating gate, there is a 3μm difference. The metal 2 layer was almost exactly 2μm, so this shows an extra 1μm left for the air gap; however, the air gap under actual diaphragms is closer to 2μm. The sacrificial resist layer had some overlap over the unetched ILD. This would bring the overlying metal 2 an extra 1μm above the rest. Some tension in the Al layer would then pull the center of the diaphragm to the same height as the highest metal 2 when the resist was removed and the metal weekend from the openings.

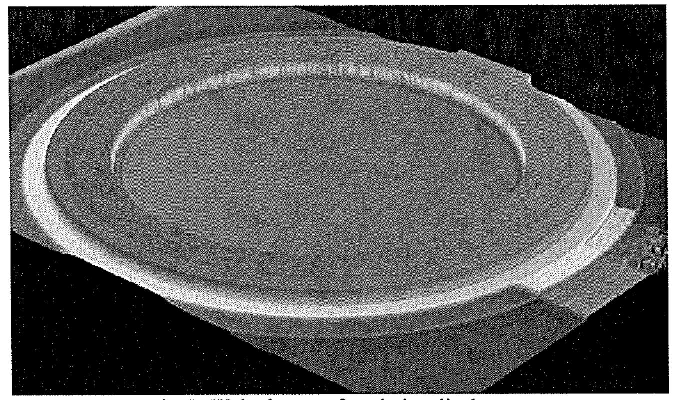

Fig. 7: Wyko image of a missing diaphragm.

V. CONCLUSION

A surface micro-machined pressure sensor was manufactured. The devices could not be tested due to a short between the control gate and the substrate, but a process of producing a surface process diaphragm was demonstrated. The diaphragms were shown to hold good structure and be very flat across the entire diaphragm. The resist was completely removed from under these devices by using an O_2 plasma. With a few process changes to remove the shorting issue a working pressure sensor should be able to be manufactured. If amplification circuitry was then added to the chip, these devices even have the capability of being microphones.

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