LOW POWER STRAIN SENSING USING TUNNELING CURRENT THROUGH MOS CAPACITORS

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ABSTRACT

Although MEMS pressure sensors and accelerometers have been widely researched and commercialized for decades, the recently increasing requirement for low power sensors is motivating research on new techniques. We present a new technology to make very low power sensors by measuring the tunneling current (I_g) through a MOS capacitor. The tunneling current can be in the nano-amp range, which is a good alternative for low power sensing. We demonstrate a power consumption of couple of nano-Watts (nW) with a minimum detectable strain of 0.0005%. This method can be used to create very low power sensors compared to typical piezoresistive and capacitive sensors whose power is typically in the μ W to mW range. Our fabrication process is very simple and compatible with CMOS processes.

INTRODUCTION

Increasing requirement of low power sensors in the portable electronics and other battery powered devices is motivating research on new technologies. Piezoresistive and capacitive sensing technologies are the most common technologies, which have been widely used to measure strain, pressure and acceleration [1, 2]. They both typically consume power from μ W to mW [3]. Considering the piezoresistive sensors, to achieve low power consumption, we have to decrease doping concentration. For example, to have a minimum detectable strain of 0.0005% (which is our device's resolution), the doping concentration should be around 10^{16} atoms/cm³ [4]. This doping concentration gives a resistivity of 1 ohm-cm. The tunneling current can be in the nano-amp range and results in a resistivity of 10^{13} ohm-cm, which is a good alternative for low power sensing. Besides adopting tunneling through MOS capacitor, tunneling sensors also employ tunneling current through an air gap between a tip and a plate [5-7]. However, their fabrication process is complex, the response is nonlinear, they require closed-loop control, and the reliability is impacted due to deterioration of the tip. Our technique may overcome these challenges.

Fig.1 shows the fabrication process of a cantilever beam with a tunneling oxide. The starting wafer is a heavily doped P-type (100) Silicon wafer. A 500 nm thick thermally grown oxide layer is patterned by wet etching. Then, a thin oxide layer (3.9 nm) is grown with an area of 1 mm². Finally, Aluminum is sputtered and patterned as contacts.

Fig.1 fabrication process

THEORIES

Since the SiO₂ is 3.9 nm thick, the main tunneling current is direct tunneling when the voltage is lower than 2.5V. When a positive voltage is applied on Al, the tunneling current comes from the electrons tunneling from Si to Al as shown in Fig. 2(a). The MOS capacitor's tunneling current through the Silicon dioxide is determined by (1) the energy barrier height between the Silicon conduction band edge and the SiO₂ conduction band edge; and (2) the electrons' out of plane effective mass [8-10]. When a [110] uniaxial tensile strain is induced, the conduction band edge of Silicon is lowered. The six-fold degenerate conduction band valleys are split into two groups, the two-fold degenerate $\Delta 2$ valleys and the four-fold degenerate $\Delta 4$ valleys. $\Delta 2$ valleys have a lower energy which cause the electrons to repopulate in the $\Delta 2$ valleys, and electrons in them have a heavier out of plane effective mass. As a result, both effects decrease the tunneling current. On the contrary, as a [110] uniaxial compressive strain is induced, the energy barrier is decreased and $\Delta 4$ valleys has a lower energy and a lighter out of plane effective mass, so the tunneling current is increased.

Fig. 2 Tunneling current in the MOS capacitor. (a) electrons tunnel from Si to Al with positive applied voltage at Al; (b) electrons tunnel from Al to Si and holes tunnel from Si to Al with negative applied voltage at Al

When a negative voltage is applied on Al, the tunneling current is composed by electrons tunneling from Al to Si and holes tunneling from Si to Al as shown in Fig. 2(b). Because the barrier height for holes is higher than that for electrons, the tunneling current mainly depends on the electrons. The tunneling current is then only determined by Al's work function. Uniaxial tensile strain causes Al's work function to decrease, so the tunneling current increases. Uniaxial compressive strain causes Al's work function to increase, so the tunneling current decreases [11].

EXPERIMENT

Fig.3 shows the measurement setup. One end of the beam was glued to a metal stage by conductive epoxy, while the other end was deformed by scrolling a micrometer. The micrometer positions are converted to strain. The tunneling current was recorded by an HP4156c Semiconductor Parameter Analyzer. Both uniaxial tensile strain and uniaxial compressive strain are in the [110] direction. The tunneling currents in the accumulation (-1V), depletion (0.5V) and inversion (1V and 2V) regions were measured.

Fig.3 photograph of measurement setup

All the measurements were done by increasing the strain from 0% to 0.112% at the step of 0.016%, and then decreasing the strain from 0.112% to 0% at the step of 0.016%. Each step has 25 samples with a sampling time of 2 seconds. The voltage applied on the device is constant voltage.

RESULTS AND DISCUSSION

Table I analysis of experiment data

Voltages	Avg (nA)	SD (A)	Drift rate (%)	SD avg (%)	$\Delta I_g/I_g$ (%)	GF
2V(tensile)	76.22	1.7E-11	5.7	0.022	-2.5	22.3
1V	1.415	1.0E-13	1.55	0.007	-2.2	19
0.5V	0.031	2.3E-13	-1.3	0.7	-0.62	5.6
-1V	0.147	3.6E-13	-6.5	0.24	0.38	3.4
2V(compress)	75	2.0E-11	5.2	0.026	2.1	19
1V	1.085	4.4E-13	7.6	0.04	1.8	16
0.5V	0.039	1.5E-14	-5.8	0.038	1.2	11.2
-1V	0.155	1.1E-13	-18.5	0.07	-0.38	3.4

The results of tensile strain and compressive strain are given

in the figure 4 & 5 and figure 6 & 7 respectively. In each figure, strains are shown on the top. Table I gives several analysis for the measurement results. The blue solid lines are the tested currents, which are not constant but drifting with time. Since in the beginning the currents decrease or increase sharply, all the drift rates are calculated from 50 seconds to 800 seconds. Because of the drift, it is uneasy to have a clear vision of how currents change versus strain especially for low voltages. We eliminate the drift of the tested current according to the slope of the current curve. The tested currents after drift correction are plotted by dashed red line. There are some spikes in the tested results of 1V, 0.5V and -1V. These spikes appear at the time that the strains are changed, so they are introduced by human body and can be ignored in the analysis.

Tensile strain

In Fig. 4, as the theories predict, increasing tensile strains cause the current to decrease at the positive voltages. In the other hand, increasing tensile strains cause the current tunneling from metal to Silicon to increase at the negative voltages. The $\Delta I_g/I_g$ at the strain of 0.112% at 2V (inversion) and 1V (weak inversion) are much larger than that at 0.5V (depletion). The $\Delta I_g/I_g$ at the strain of 0.112% at -1V is very small.

Fig. 4 tunneling current change versus tensile strain

From the analysis in the Table I and Fig. 5, we can see that the average current (avg) without strain decreases as the voltage decreases. The noise or the Standard Deviation (SD) of the currents decreases two orders of magnitude from 2V to 1V, while it keeps the same order of magnitude from 1V to 0.5V. The resolution the device is calculated by the equation of SD/avg. The SD/avg at 2V is 0.022%. The $\Delta I_g/I_g$ at the strain of 0.112% at 2V is -2.5%. As a result, the minimum detectable strain at 2V is around 0.001%. Likewise, the minimum detectable strain is around 0.0005% at 1V. The SD/avg at 0.5V and -1V are so close to the $\Delta I_g/I_g$ at the strain of 0.112% that the minimum detectable strains are around 0.112%, which are also obvious from the figures. So the SD/avg and the $\Delta I_g/I_g$ at the strain of 0.112% determine the minimum detectable strain.

The current drifting is observed. The drift rate is defined as

the normalized current changing from 50s to 800s. In the table, the drift rate decreases as the voltage decreases. However, the currents increase at 2V and 1V, while it decreases at 0.5V and -1V. It is likely that the current may change very slowly at some voltage between 1V and 0.5V.

The gauge factor (GF) also shows that 2V and 1V have better performance than 0.5V and -1V, and the GF at 2V and 1V are in the same range as a piezoresistive sensor.

Fig. 5 tunneling current versus time at tensile strain

Compressive strain

From Fig. 6, we can see that the compressive strain responses are contrary to the tensile strain responses. Increasing compressive strains cause the current to increase at the positive voltages, while increasing compressive strains cause the current tunneling from Aluminum to Silicon to decrease at the negative voltages. Unlike the tensile strain, the $\Delta I_g/I_g$ at the strain of 0.112% doesn't decrease largely from inversion to depletion at positive voltages.

The $\Delta I_g/I_g$ at the strain of 0.112% at the negative voltage is still very small like the tensile strain.

Since the tunneling currents are the same as the tensile strain experiment, the avg and SD should be close to those of tensile strain. However, the SD at 1V is 4 times larger than that of tensile strain, while the SD at 0.5V is ten times smaller and the SD at -1V is three times smaller. The difference may come from the electrode contact or environment like temperature, since the compressive strain measurement were conducted at different time. As a result, the SD/avg at 1V is 0.04%. Since the $\Delta I_g/I_g$ at 1V is 1.8%, the minimum detectable strain at 1V is around 0.0025%. Likewise, the minimum detectable strain at 2V is around 0.0013%.

The drift rate should also be the same as the tensile strain. However unlike drift rate of the tensile strain, the drift rate doesn't become smaller when the voltage goes smaller. The currents still increase at 2V and 1V, while it decreases at 0.5V and -1V.

The GF at 2V and 1V are better than those at 0.5V and -1V.

Fig. 6 tunneling current change versus compressive strain

Fig. 7 tunneling current versus time at compressive strain

Discussion

Considering both tensile and compressive strain, a voltage at 2V consumes a power of hundreds of nW with a minimum detectable strain of 0.001% for both strains. A voltage at 1V consumes only 1~2 nW with a minimum detectable strain of 0.0005% for tensile strain and 0.0025% for compressive strain. However the SD should be the same for both tensile and compressive strain, with better electrode contact, the minimum detectable compressive strain at 1V should be also around 0.0005%.

The drift requires further study since it influences the accuracy a lot. If the drift comes from the Fowler-Nordheim tunneling, thinner oxide layer may reduce the drift. If the drift comes from the interface or trap assistant tunneling, better quality oxide should be able to reduce the drift.

CONCLUSION

We demonstrate a tunneling strain sensor with a low power consumption of several nW as well as a minimum detectable strain to 0.0005%. The power consumption can be reduced from hundreds of nano-Watts to several nano-Watts as the voltage decrease. Since the SD/avg is getting larger when the voltage decreases, the resolution becomes worse. So there is a balance between the power consumption and the resolution. The device performs best in the inversion region, where the electrons tunnel from Silicon to Al. The gauge factor of our tunneling sensor is in the same range as a piezoresistive sensor. The fabrication process is simple and CMOS compatible.

It seems like that the drift and the noise determine the performance of the tunneling sensor. The drift causes the accuracy to be time dependent, so a further study of the drift is necessary. The noise determines the resolution, so a very low noise read out circuit is demanded.

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