ABSTRACT

We demonstrate the first-ever pressure sensor utilizing graphene piezoresistors demonstrating the sensitivity as high as 323 µV/V/mmHg. This sensitivity is two orders of magnitudes higher than that of the reported carbon nanotube based transducers [1]. Our sensor consists of a 400nm Si₃N₄ membrane on silicon substrate with 10nm/140nm thick Cr/Au electrodes on top where the graphene layer is transferred on top of this structure. Our pressure sensor highly nonlinear, but can still be useful for applications where ultra-high sensitivity is needed and table lookup can be used.

INTRODUCTION

Piezoresistive pressure sensors are common devices used in biomedical to industrial monitoring applications. The small gauge-factor of the piezoresistive resistors, which are placed in a Wheatstone bridge configuration, limits the sensitivity of a given sensor. The gauge-factor, the membrane thickness, and the required sensitivity for a given application determine the pressure sensor membrane length, width, and thickness. A much higher gauge-factor and transducer sensitivity would enable a smaller sensor for constant sensitivity, or would enable a much more sensitive sensor for constant membrane area (Figure 1). Calculations in this figure are based on the equation (1) [2] for circular membrane pressure sensors where a is the diameter, h is the thickness, G is the gauge-factor, ν is the Poisson’s ratio, and E is the Young’s modulus.

\[
\frac{\Delta V}{V} = G \frac{3}{8} \left(1 - \nu^2\right) \left(\frac{a}{h}\right)^2
\]

Previous efforts have utilized electrodes or probes applied over the graphene films and then apply stress to the solid substrate to realize strain in the graphene films [8]. In this paper, we placed the graphene films over the electrodes defined over low-stress Si₃N₄ membranes using a film transfer method. In this method, the graphene film is poly-crystalline with a grain size ranging from 50-800 nm, and can be two or three layers thick. The Si₃N₄/electrode/graphene film stack membranes were actuative using a piezoelectric actuator at resonance to obtain high strains, and the resulting change in resistance was used to measure the gauge factor [5]. Optical interferometer was used to measure the displacement.
as a result of PZT actuation, and the displacement was used to determine the strain. A very large gauge factor of 11289 was obtained. This is two to three orders of magnitude higher than that of most other materials which would enable piezoresistive transducer SNR to be higher by the same factor, making piezoresistive transducers much more attractive than other transduction mechanisms such as electrostatic or piezoelectric sense transducers. For example, for electrostatic transduction, the high sensitivity often occurs by decreasing gaps, but that often occurs at the cost of dynamic range and linearity. Piezoelectric films often require thicker films to obtain higher charge for a given film thickness, and do not scale well at the nanoscale.

DEVICE FABRICATION

Our device fabrication (Figure 2) starts with formation of a 400 nm low-stress LPCVD silicon-nitride on a 4-inch <100> p-type silicon substrate followed by anisotropic etching of the silicon substrate. A stack of Cr (10nm)/ Au (140nm) is then evaporated and patterned using thermal evaporation to form a four-point probe structure. This structure consists of four wires on each side of the membrane converging from gaps of 10µm to 1µm. A 0.5µm thick SiO₂ film is sputtered and patterned over the electrodes so only the end section of electrodes are exposed. A CVD deposited [9] graphene-on-copper layer is transferred on top of the electrodes. The process of graphene transfer involves spinning a thin (300nm) PMMA on top of graphene followed by wet etching of the copper foil. The silicon wafer which includes the nitride membranes is used to lift the PMMA/graphene bilayer floating on top of the Cu etch beaker. Acetone is used to remove the PMMA and samples are cleaned within DI water and let to dry for 6 hours. A PZT plate is adhesively attached to the back-side of the silicon die, with two wires soldered to the PZT plate. The Raman spectrum of the graphene films indicates a high quality film owing to the large G-to-D ratio. The D map is associated with defects in graphene [9]. The sheet resistance of the graphene film is 765-1500 Ω/sq, measured over 10 samples.

PRESSURE SENSITIVITY MEASUREMENTS

Measurement system consists of a syringe pump in series with two controlling valves, attached to the backside of the cavity and used to induce constant strain on graphene/Si₃N₄ composite plate (Figure 3).

![Figure 3: Schematic (a) and image (b) of measurement system including syringe pump, strain gauge, and leveling stage, and commercial pressure for calibration.](image)

PRESSURE INDUCED STRESS SIMULATION

Simulations are performed using finite element package ABAQUS for the entire PZT/Silicon/Membrane structure. Plane strain analysis is used here due to the relatively large lateral dimensions of the structure, compared to its thickness, which gives

![Figure 4: SEM image of 4-point probe electrodes on a silicon nitride membrane to measure pressure response from graphene layer placed in the oxide box (a and b), and schematic of this structure is in (c).](image)
good agreement with preliminary 3D simulations. The mode shape was obtained with assumed in-plane stress in the nitride membrane. A stress of 220MPa gives good agreement with the experiments and is within the expected range of stress obtained during fabrication. Steady state dynamic simulations were used to obtain resonance response of the structure. While nonlinear geometric effects are considered in the simulations, the PZT is modeled with a built-in linear model.

EXPERIMENTAL RESULTS

The resistivity increases at both compressive and tensile strains which shows the graphene bends the same way regardless of the pressure direction in our present sensor configuration. Optical interferometer measurement of membrane displacements (Figure 9) indicates that the center part of the membrane moves similarly at positive and negative pressures due to pre-stress from SiO$_2$ layer. The measured graphene gauge factor is orders of magnitude higher than that of most piezoresistive materials used in MEMS such as doped polysilicon and metals. Doped polysilicon can have gauge factors on the order of 30-40, while metals have a gauge factor of 55 [10-11].
If the measured relative resistance is plotted against the estimated strain, the slope of the line is the gauge-factor (Figure 10).

Resistivity changes of the graphene film as a function of vacuum up to 5mmHg and positive pressures up to 6mmHg are plotted in Figure 11. The highly nonlinear behavior may be due to the fact that for either compressive or tensile stress the graphene membrane is stretched in the same direction. Another mechanism could be the generation of Si$_3$N$_4$ polarization charge is of the same variety whether the stress is compressive or tensile.

CONCLUSION

In summary, we present a pressure sensor process flow and results that pave the way for ultras-high sensitivity pressure sensors. Our estimated gauge-factor for this sensor is 11,300 matching that recently measured with AC resonance measurement of the graphene film [5]. However, we are exploring the exact reason for the nonlinearity, which maybe tunable for linear devices by adjusting the fabrication process.

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REFERENCES


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