INTEGRATION OF GRAPHENE-POLYMER HETEROSTRUCTURE MEMBRANES INTO A MULTI-USER MEMS FABRICATION PROCESS

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ABSTRACT
Graphene-polymer heterostructure (GPH) membranes are an emerging high-performance option for MEMS. Here we demonstrate for the first time how GPH membranes can be integrated into commercial multiuser MEMS fabrication using the PiezoMUMPs process, to create capacitive pressure sensors and CMUTs. The pressure sensors demonstrate a linear areal sensitivity of 32 $Pa^{-1}mm^{-2}$ over a dynamic range of 200 kPa. The CMUTs possess 9.6 MHz resonance frequency and Q factor of 10 under a bias of 2 V, which is ideal for medical and non-destructive testing applications. This is the first demonstration of an industry-standard process for the fabrication of graphene-based MEMS devices.

KEYWORDS
Graphene, NEMS, MUMPs, CMUT, pressure sensor

INTRODUCTION
Graphene-based MEMS show immense promise as highly sensitive, low power and robust devices, owing to graphene's high Young's modulus (1 TPa), elastic stretching up to 20% strain, low areal mass, high carrier mobility and high fracture strength (42 Nm^{-1}) [1]. There are many challenges to achieving commercially viable, high-throughput manufacturing of graphene-based MEMS devices. Depositing an ultra-thin conformal 2-chloro-p-xylylene (parylene-C) support layer onto monolayer CVD graphene to form a GPH membrane has been shown to increase the number of intact and functioning membranes, whilst largely retaining graphene's conductivity and desirable mechanical properties.[2-4]

Multi-user MEMS fabrication processes provide mass-producible MEMS using standard micromachining processes. PiezoMUMPs is a variation of the SOI MUMPs process with a top layer of aluminium nitride (AlN) deposited by reactive sputtering. Here we demonstrate for the first time the compatibility of GPH membranes with wafer-scale mass-producible MEMS to produce capacitive pressure sensors and CMUTs. The underlying MEMS chips are fabricated based on our custom design as part of a multi-project wafer (MPW). The GPH membranes are transferred onto the chips as the final fabrication step. We evaluate the capacitance vs pressure response of the GPH MEMS sensor against a reference pressure gauge. We apply DC and AC voltages across the CMUT electrodes and measure the resulting vibrations with a Laser Doppler Vibrometer (LDV) to determine its resonant frequency and Q factor to evaluate its usability as an ultrasonic transducer.

DESIGN
A schematic of a PiezoMUMPs-GPH device is shown in Figure 1a. An optical micrograph of the fabricated chip is shown in Figure 1b. The device consists of two parallel plates: a deflecting GPH membrane consisting of a CVD graphene layer and a support parylene-C layer on top, and a doped silicon crystal counter electrode. The GPH membrane is suspended over a hexagonally packed array of circular cavities in the AlN layer.

FABRICATION
Capacitive MEMS devices were fabricated by laminating a 54 nm thickness monolayer graphene-parylene GPH membrane layer onto a device base fabricated using the PiezoMUMPs process. The top silicon oxide layer was patterned and etched to create an access-via to the doped crystal silicon layer that serves as a common bottom electrode for the array. The AlN piezoelectric layer was patterned and etched to create an array of 10 µm diameter circular cavities with a depth of H = 500 nm. The final metallization step, 20 nm chrome and 1000 nm aluminium, was used to create the top and bottom contact pads for the GPH membrane and crystal silicon electrodes, respectively.

To fabricate the GPH membranes, single layer CVD graphene on SiO2/Si was coated with an ultra-thin (54 nm) layer of parylene-C. A 140 nm thick layer of PMMA (in anisole) was spin-coated onto the graphene-parylene stack, and a tape scaffold was pressed on top for support. The underside SiO_2/Si was removed through wet etching in KOH solution and the floating stacks were rinsed in three consecutive DI water baths. The stacks were removed and dried and transferred onto a clean PiezoMUMPs sensor base using a transfer arm and a hotplate. The PMMA support layer was removed by submerging in acetone, followed by a rinse in hexane. To enable electrical connectivity, the contact pads were wire bonded with a wedge bonder to a leadless chip carrier.

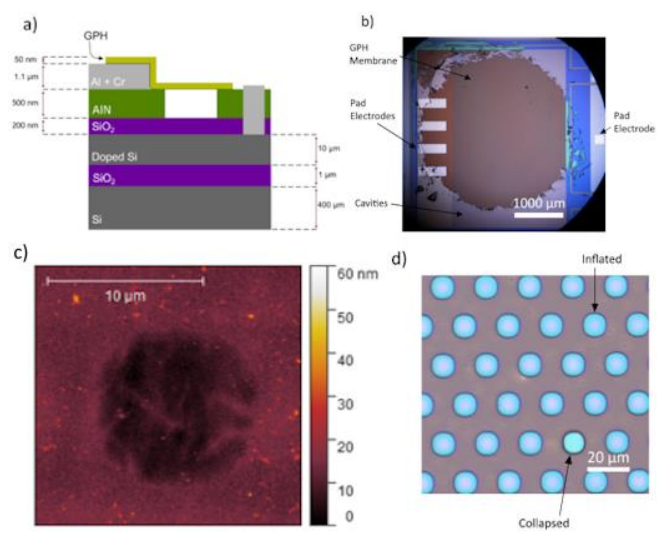

Figure 1: (a) Schematic cross section of a PiezoMUMPs–GPH pressure sensor (b) Optical micrograph of a 3.2 mm diameter GPH membrane on top of the PiezoMUMPs chip. (c) x-y AFM image of suspended GPH membrane at the equilibrium position (d) Inflated suspended circular membranes with Newton rings and one collapsed membrane.

CHARACTERISATION
Figure 1b and 1d are optical micrographs of an intact circular GPH membrane of diameter 3.2 mm after lamination onto a

PiezoMUMPs sensor base. Out of 33 membranes pictured, only 1 has collapsed, which can be noted by the inner light turquoise block colour and dark circular perimeter. Figure 1c shows the AFM topography of a circular suspended GPH membrane.

The GPH membrane laminated onto the PiezoMUMPs sensor base acts as a MEMS capacitive pressure sensor. Figure 2a compares the capacitance of a control device - a bare PiezoMUMPs sensor base - and a PiezoMUMPs-GPH sensor when the external pressure is cycled between $\Delta P = 0$ and $\Delta P = 190$ kPa. The PiezoMUMPs-GPH sensor response was found to be near linear over a dynamic range 0 - 200 kPa (Figure 2b). The sensor sensitivity was calculated as S =11.7 aF/Pa which corresponds to an areal sensitivity of 32 aF/Pa/mm^2. The sensor response was compared to that predicted by modelling of membrane deflection with the Foppl–von Karman equations, blue line Figure 2b. The simulated capacitance change was plotted up to a membrane collapse pressure Figure 3b (inset) calculated as $\Delta P = 400$ kPa. The simulation shows that near linear response continues up to 300 kPa.

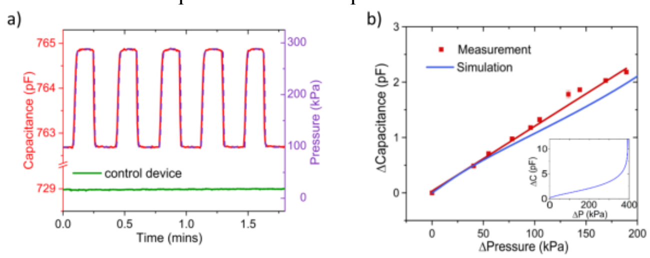

Figure 2: (a) Capacitance measurements from PiezoMUMPs devices with and without (control) a GPH membrane when the external pressure is cycled between atmospheric pressure ($\Delta P = 0$) and $\Delta P = 190$ kPa. (b) Change in device capacitance vs change in external pressure of the GPH-PiezoMUMPs sensor.

Individual cells of the PiezoMUMPs-GPH device can be configured as CMUTs. We characterized the response of individual cells under electrostatic excitation of the GPH membrane. The scanning mode of a LDV was used to capture the first axisymmetric mode of the membrane, mode (0,1), under excitation with a voltage waveform with bias and amplitude voltages of $V_{dc} = 10$ V and $V_{ac} = 5$ V and an excitation frequency of f = 10 MHz. The frequency-response curves of the RMS velocity measured at the membrane centre point under atmospheric pressure are shown in Figure 3b as the bias voltage V_{dc} was swept from 1 to 25 V then from -1 to -25 V with the voltage amplitude held fixed at $V_{ac} = 5$ V. Figure 3c shows the peak RMS displacement, corresponding to the frequency sweeps as a function of the bias voltage V_{dc}. Increasing the magnitude of the bias voltage was found to increase the peak displacement regardless of the voltage polarity. This is consistent with the first harmonic of electrostatic actuation being proportional to bias voltage. We show in Figure 3d the quality factor, extracted from the frequency-response curves of Figure 4c, as a function of bias voltage V_{dc}. The measured Q factor ranges from Q ~3 at high bias voltages to Q ~7 at low bias voltages suggesting that energy losses in the GPH cell are dominated by dissipation in air. Increasing bias voltage increases the membrane deflection and the acoustic impedance of air in the cell, thereby reducing Q.

We have demonstrated for the first time that GPH membranes can be integrated on mass-produced MPW MEMS chips to form capacitive pressure sensors and resonators. We found that the resulting devices perform favourably compared to previously demonstrated graphene pressure-sensing MEMS [3, 4] and that the membranes had a resonance frequency that is within the range of medical ultrasound. We have shown that the capacitance change of the PiezoMUMPs-GPH device can be modeled, allowing for future devices to be designed according to desired sensitivity and operable range.[5] The resonant frequency agreed with a combined stretching and bending approximation, and energy losses were dominated by dissipation in air.

Graphene MEMS have been shown to have significantly higher sensitivity, dynamic range, Q factor, and other superior performance characteristics compared to Silicon MEMS.[1] This work now enables an industry-standard multi-user, multi-wafer processing route for the development, pilot-scale fabrication and eventually commercial production of graphene-based MEMS sensors and actuators. This will allow for vastly increased device complexities and yield and offer a route to large-scale manufacturing and commercial implementation, which has not been possible thus far.

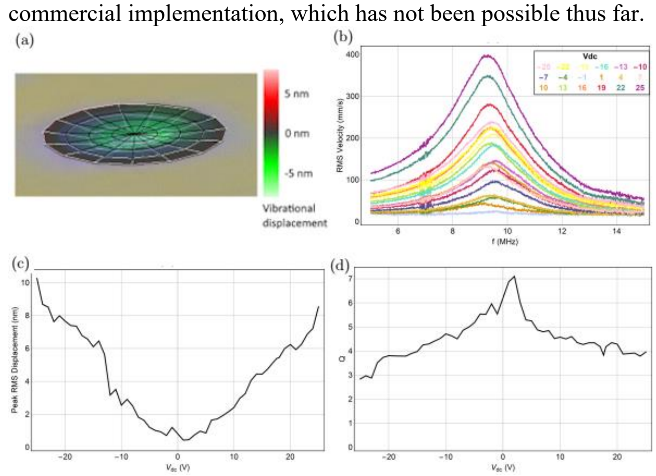

Figure 3: (a) The first axisymmetric mode of the circular membrane obtained at an excitation frequency of f = 10 MHz. (b) RMS velocity of GPH membrane against frequency for a range of DC voltages V_{DC}=-25 to +25. (c) The peak RMS displacement and (d) quality factor Q of the GPH CMUT as functions of bias voltage V_{dc}.

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