Suspended graphene variable capacitor

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Keywords: graphene, nano-electromechanical systems, NEMS, variable capacitor

Supplementary material for this article is available online

Abstract
Electromechanical variable capacitors, or varactors, find a wide range of applications including sensing applications and the tuning of electrical circuit resonance. We demonstrate a nano-electromechanical graphene varactor, a variable capacitor wherein the capacitance is tuned by voltage controlled deflection of a dense array of suspended graphene membranes. The low flexural rigidity of graphene monolayers is exploited to achieve low actuation voltage and high tunable capacitance density in an ultra-thin structure. Large arrays comprising thousands of suspensions were fabricated to give a tunable capacitance of over 10 pF mm$^{-2}$. This capacitance density suggests that graphene offers a potential solution to the challenge of reducing the size of micro-electromechanical systems (MEMS). A capacitance tuning of 55% was achieved with a 10 V actuating voltage, exceeding the 50% tuning limit of Hookean parallel plate pull-in without the use of complex mechanical schemes that occupy substrate area. Capacitor behavior was investigated experimentally, and described by a simple theoretical model. Mechanical properties of the graphene membranes were measured independently using atomic force microscopy. We present a comparison of state-of-the-art MEMS and graphene varactors. The quality factor of graphene varactors is limited by graphene sheet resistance, pull-in voltage can be improved with more aggressive scaling, while the power handling and cycling stability of graphene varactors remains unknown.

Mechanically tuned variable capacitance has been an effective means to tune resonant circuits since the advent of radio [1]. More compact varactors have since been developed in the form of an electrically tuned semiconductor junction capacitance [2]. Micro-electromechanical system (MEMS) implementations of varactors [3] combine the advantages of mechanical and semiconductor varactors in a single device architecture, including high electrical quality factor, high linearity, and the capacity for monolithic integration with silicon electronics [4]. The canonical MEMS varactor is the parallel plate structure consisting of a conducting membrane suspended over a fixed plate, actuated by electrostatic attraction under an applied bias potential. While simple in structure, typical parallel plate varactors suffer high operating voltage [5, 6] and a limited capacitive tuning range. These limitations are typically overcome by complex mechanisms [7], which increase both the size and actuation voltage. Another disadvantage of MEMS varactors is their requirement for designated, specially designed suspensions because the varactor plate is itself typically too thick for deflection. These designated suspensions occupy additional space that reduces the density of tunable capacitance. Moreover, the thickness of traditional MEMS varactors and their large gaps (usually >1 µm) requires larger vertical space, particularly when integrated with silicon circuits.

Fundamentally, increasing the flexibility of a suspended element by reducing it’s thickness will reduce the actuation voltage of a parallel plate varactor [8]. Monolayer graphene membranes achieve the ultimate limit with an inferred elastic stiffness of $E_c \approx 390$
In comparison a 15 nm thick Si$_3$N$_4$ membrane has an elastic stiffness of $E_c \simeq 6.3 \text{kN m}^{-1}$. Low elastic stiffness also alleviates the need for designated suspensions, therefore graphene nano-electromechanical systems (NEMS) can occupy less area than traditional MEMS counterparts [10]. Graphene devices can be easily integrated with integrated silicon electronics using standard transfer techniques [11, 12]. In the last decade, electrostatic actuation of graphene has been demonstrated [13] and graphene NEMS have been widely investigated, including suspended graphene resonators [14–16], switches [17–19], and sensors [9]. While the theoretical limits of suspended graphene varactors has been investigated [8], large arrays of low spring constant suspensions has been plagued by low fabrication yield [20]. In this letter we report the fabrication and characterization of suspended graphene varactors. Each fabricated device is an array of over 1000 suspensions. The total tunable capacitance of each varactor is $C_v \geq 1 \text{pF}$. The active area of the fabricated varactor is only 400 nm thick.

The varactors were fabricated by the process illustrated in figure 1(A), consisting of three stages. The first stage is substrate preparation. Low resistivity Si wafers with 300 nm of thermal SiO$_2$ were metallized and trenches were etched. The second stage is graphene growth and pre-patterning. Growth on Cu foils was performed by chemical vapor deposition, followed by photolithography and dry etching of graphene strips, and lastly a polymethylmethacrylate handle was used during a sacrificial Cu etch. In the final stage, graphene was transferred atop the trenches in a wet process with the suspensions released by critical point drying. Further processing details are provided in the supplementary information. A schematic of the fabricated device is illustrated in figure 1(A). Trenches of depth $h = 155$ nm depth and length $L = 2.5$ $\mu$m were fabricated, in arrays of at least 20 by 50 suspensions with an areal density of tunable capacitance up to 12 $\text{pF mm}^{-2}$. The active area of graphene suspensions constitutes 20% of the total device area.

The varactor capacitance was measured in a vacuum probe station, as schematically shown in figure 2(A), including both the fixed parasitic capacitance $C_p \sim 14.8$ $\text{pF}$ and tunable capacitance $C_v \sim 1$ $\text{pF}$. The decomposition between parasitic and tunable capacitance was determined on the basis of voltage dependent measurements of total capacitance. A semiconductor parameter analyzer was used to measure the capacitance with an ac excitation of $V_{ac} = 30$ mV at a frequency $f = 100$ kHz while a dc bias voltage $V_{dc}$ was swept to tune capacitance by electrostatic actuation of the suspended graphene membranes.

Figure 2(B) shows the typical behavior of tuned capacitance $\Delta C_v/C_v$ versus bias $V_{dc}$ for a typical graphene varactor among the five devices tested. At a bias...
voltage $V_{dc} = 10 \text{ V}$, the capacitance change is 55%, exceeding the 50% pull-in limit of a Hookean parallel plate varactor [6]. The 55% tuning range is determined with respect to the actuated capacitance $C_v$ alone. The total measured capacitance versus bias voltage, shown in the inset of figure 2(B), includes all parasitic capacitance contributions, the majority of which are due to on-chip wiring and large area electrodes necessary for interrogation by probe station. Integration for on-chip interrogation will eliminate these parasitics. The fixed, unactuated capacitance between the unactuated graphene and underlying Si electrode can be minimized by reducing trench spacing and by replacing the global Si actuation electrode with local actuation electrodes within the trenches. The measured capacitance curves agree well with a virtual displacement model imposing a balance of stretching, pre-tension and electrostatic forces on a graphene membrane,

\[
\frac{Et\pi^{\delta^3}}{8L^4(1 - \nu^2)} + \frac{8C_i S_0 \delta}{L^2} = \frac{eV_{dc}^2}{(h' - \frac{\delta}{V_{dc}})^2},
\]

where the membrane shape is approximated with a half-cosine, $E$ is the graphene Young modulus, $S_0$ is the pre-tension, $t = 3.35 \text{ Å}$ is the graphene thickness, $\nu = 0.141$ is the graphene Poisson ratio, $C_i = 2$ is a constant dependent on membrane aspect ratio [23], $h' = 192 \text{ nm}$ is the electrical length between Si substrate and graphene membrane, and $\delta$ is the graphene membrane deflection induced by applied bias $V_{dc}$. The capacitance $C_v$ is simply expressed in terms of the deflection [8],

\[
C_v = \frac{4WL\epsilon_0}{\pi h' \sqrt{1 - \delta^2/h'^2}} \cdot \arctan \left( \frac{h' + \delta}{h' - \delta} \right).
\]

Fitting the experimentally measured capacitance versus bias voltage, we extract a Young’s modulus $E = 180 \text{ GPa}$ and a pretension $S_0 = 40 \text{ mN m}^{-1}$. Both $E$ and $S_0$ are lower than that reported in experiments with individual exfoliated graphene membranes [14].

The ambivalent response of the varactor to the applied bias $V_{dc}$ was measured, as shown in figure 2(C). Low hysteresis was observed for a 10 V swing of $V_{dc}$ of either polarity. The nonlinearity of the ambivalent response leads to odd harmonic generation in the resulting current spectrum, since the total ac current $I_{ac} = C_dV/\text{dt} + V\text{d}C/\text{dt}$, where $\text{dC}/\text{dt} = \text{dC}/\text{d}\delta \cdot \text{d}\delta/\text{dt}$. We measured the third harmonic current $I_{ac}(3f)$ with a lock-in amplifier tuned for ac excitation $V_{ac} = 1–10 \text{ V}$ at a frequency of $f = 20 \text{ kHz}$. The measured $I_{ac}(3f)$ versus $V_{ac}$ is plotted in figure 2(D). A simple model for $I_{ac}$ employing a quasi-static approximation for $\text{d}\delta/\text{dt}$ ignoring inertial effects leads to excellent agreement with measured

Figure 2. (A) The schematic of the capacitance measurement setup in a vacuum probe station, including both variable and parasitic capacitance of the varactor, $C_v$ and $C_{vp}$, respectively. (B) The relative change in capacitance $[C_v(V_{dc}) - C_v(0)]/C_v(0)$ versus bias $V_{dc}$ as measured with $V_{ac} = 30 \text{ mV}$ at $f = 100 \text{ kHz}$ and best-fit to a simple analytical model. The best-fit model parameters are $S_0 = 40 \text{ mN m}^{-1}$ and $E = 180 \text{ GPa}$. The inset depicts the total measured capacitance versus bias voltage. (C) The change in varactor capacitance $[C_v(V_{dc}) - C_v(0)]$ versus $V_{dc}$, illustrating ambivalent operation. The measurement shows forward and backward sweeps with no hysteresis. (D) The third harmonic current $I_{ac}(3f)$ versus $V_{ac}$, as measured and with a simple analytic model with no fit parameters. The modulus $E$ and pre-tension $S_0$ were determined from $C_v$ versus $V_{dc}$. 

\[
\frac{Et\pi^{\delta^3}}{8L^4(1 - \nu^2)} + \frac{8C_i S_0 \delta}{L^2} = \frac{eV_{dc}^2}{(h' - \frac{\delta}{V_{dc}})^2},
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where the membrane shape is approximated with a half-cosine, $E$ is the graphene Young modulus, $S_0$ is the pre-tension, $t = 3.35 \text{ Å}$ is the graphene thickness, $\nu = 0.141$ is the graphene Poisson ratio, $C_i = 2$ is a constant dependent on membrane aspect ratio [23], $h' = 192 \text{ nm}$ is the electrical length between Si substrate and graphene membrane, and $\delta$ is the graphene membrane deflection induced by applied bias $V_{dc}$. The capacitance $C_v$ is simply expressed in terms of the deflection [8],

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\]
results without any free fitting parameters. Notably, at $V_{ac} = 1\, \text{V}$ the ratio $I_W (f) / I_W (3f) = 220$, corresponding to less than $46\, \text{dB}$ third harmonic distortion in the varactor response.

Our low frequency measurements indicate that the graphene sheet resistance $R_s \approx 7200\, \Omega/\Box$, leading to high series resistance, degrading the electrical quality factor $Q$ at radio frequencies. The total series resistance of the varactor prior to actuation (at $0\, \text{V}$) was $R \approx 609\, \Omega$ and at maximum actuation ($10\, \text{V}$) it was $R \approx 660\, \Omega$, with the variation owing primarily to field effect modulation of carrier density within the graphene. The corresponding quality factors at 100 kHz are $Q = 165$ and 147, respectively. While theoretical analysis [8] indicates that radio frequency operation with $Q > 200$ at 10 GHz can be achieved by using chemically doped graphene with $R_s \approx 125\, \Omega/\Box$ [24].

Experimental realization of such high quality factors at high frequencies requires not only a reduction in graphene sheet resistance, but also the integration of the graphene varactor with a low-loss microwave compatible structure.

Atomic force microscopy (AFM) was used to independently verify the mechanical properties of individual suspended graphene membranes. Contact mode AFM images were first taken of the varactor, as shown in figures 3(A) and (B). Force-deflection measurements [25] were then conducted on 33 individual membranes, several of which are indicated in figure 3(B). A variety of membranes were selected, including several that underwent partial collapse following high voltage testing of varactor response. The deflection of a silicon cantilever with a calibrated spring constant ($k_{cant} = 0.916\, \text{N m}^{-1}$) was measured as a function of the piezoelectric driven extension of the AFM, from which the force–displacement curve was inferred. Figure 3(C) depicts a typical measurement of applied force $F$ versus graphene membrane displacement $\delta$. For deflections $\delta < 25\, \text{nm}$, a linear fit determines the effective spring constant $k_{\text{graphene}}$ per Hooke’s law. Pre-tension $S_0$ dominates in the linear regime, and was estimated according to the beam approximation under a point load, $k_{\text{graphene}} = (\pi^2/2)S_0 W/L$. The pre-tension $S_0$ of 12 membranes are illustrated in figure 3(E) versus $W/L$. Nonlinearity in applied force versus deflection was observed at larger deflections due to graphene stretching, with an example illustrated in figure 3(D). The force versus deflection relation $F \propto \varepsilon E^3$ can be modeled for different geometries with a virtual displacement method (details provided in supplementary information), allowing a numerical fit to measurements and extraction of the Young’s modulus $E$. The Young’s modulus $E$ of 14 membranes are illustrated in figure 3(F) versus $W/L$, yielding a mean $E = 140 \pm 60\, \text{GPa}$ in good agreement with the value

![Figure 3](image)
There are several critical characteristics and figures of merit that describe a MEMS variable capacitor. In Table 1 we compare our experimentally realized graphene varactor with a variety of previously reported MEMS designs. The linearity figures in Table 1 were calculated using the correlation formula in \([30, 35]\). As shown in Table 1, although our graphene varactor offers higher capacitance density, lower thickness, and improved linearity, further improvement is required in two important aspects: high frequency quality factor and wider capacitance tuning range. As noted previously, high frequency quality factor is limited by graphene sheet resistance \([8]\). The adoption of chemically doped graphene and a radio frequency compatible waveguide assembly would greatly enhance the quality factor. The tuning range of graphene varactors could be improved, at the expense of capacitance density, through complex mechanical schemes similar to those used in other MEMS structures, \([31, 34]\). Importantly, the adoption of graphene varactors for radio frequency applications would necessitate an understanding of both power handling capability and cycling stability. There is insufficient experimental data at the present time to determine whether graphene varactors are capable of the power handling and cycling stability required for radio frequency applications.

We finally consider a comparison of varactor air gap and area required to achieve \(C/V = 1 \text{ pF} \text{ mm}^{-2}\) in Figure 4, including the suspended graphene design and other state of the art MEMS designs from Table 1. The suspended graphene varactor offers the highest capacitance density and linearity, but further improvement is required in high frequency quality factor and wider capacitance tuning range. As noted previously, high frequency quality factor is limited by graphene sheet resistance \([8]\). The adoption of chemically doped graphene and a radio frequency compatible waveguide assembly would greatly enhance the quality factor. The tuning range of graphene varactors could be improved, at the expense of capacitance density, through complex mechanical schemes similar to those used in other MEMS structures, \([31, 34]\). Importantly, the adoption of graphene varactors for radio frequency applications would necessitate an understanding of both power handling capability and cycling stability. There is insufficient experimental data at the present time to determine whether graphene varactors are capable of the power handling and cycling stability required for radio frequency applications.

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density in the smallest vertical space. Improving the active area occupation of total device area beyond 20% will further increase the capacitance density of the graphene varactor. At 100% active area occupation, the areal capacitance density reaches the limit imposed by the permittivity of free space, $C/A = \varepsilon_0/\hbar$. The ultimate limit to the achievable areal capacitance density of suspended graphene will be determined by the minimum trench depth $h$ that can be sustained without spontaneous pull-in by Casimir–van der Waals forces. The criterion for spontaneous pull-in by Casimir–van der Waals forces [26] in the ideal conductor limit is $RL^2/Eth^2 < 0.245$ with $R = \hbar c/240$. For a trench aspect ratio $L/h = 10$, a minimum trench height of $h = 10\text{ nm}$ and maximum capacitance density $C/A = 890 \text{ pF mm}^{-2}$ can be theoretically achieved.

In conclusion, we have demonstrated large area suspended graphene varactors, reaching a 55% tuning range with a 10 V actuation voltage, a high device yield $>95\%$ and an areal capacitance density of 12 pF mm$^{-2}$. Further reduction in pull-in voltage may be achieved by increasing the trench aspect ratio $L/h$, but avoiding spontaneous pull-in by Casimir–van der Waals forces will require increased height $h$, and thus reduced areal capacitance. The application of graphene varactors to radio frequency circuits requires the challenge of monolithic integration to be addressed through more advanced fabrication processes, the adoption of low sheet resistance graphene for improved quality factor, and an understanding of limitations to power handling and cycling stability.

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