A Large Scale Fabrication of Graphene Based Nano-electromechanical Contact Switches With Ultra-low Pull-in Voltage

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Nano-electromechanical (NEM) contact switches have been extensively studied to suppress the limitations of conventional complementary metal-oxide-semiconductor (CMOS) transistors. The attributes of NEM contact switches includes reduced power consumption, reduced off-state leakage current, increased on-state current and sub-thermal switching. However, unacceptably high pull-in voltage and low contact lifetime posed a significant challenge for the use of NEM contact switches in energy efficient CMOS applications. Here, we demonstrate a graphene-based electro-statically actuated NEM contact switches with ultra-low pull-in voltage and significant improvement in the contact lifetime. This was achieved by using the graphene on gold electrode as a contact material. The graphene NEM contact switches with graphene as a contact material exhibits an ultra-low pull-in voltage of <0.5 V and high contact lifetime of more than $1.5 \times 10^6$ cycles. The switches also showed an excellent switching performance with high on/off ratio of $\sim 10^8$, an extremely low off-state current of $\sim 100 \text{fA}$, and small hysteresis window of $< 0.1 \text{V}$.

1. Introduction

The CMOS based silicon industry is continually demanding energy efficient performance and low power utilization in CMOS devices for its new era of applications, such as the Internet of Things (IoT) and smart dust [1, 2]. As a result, the NEM contact switches emerge as one of the attractive alternatives to CMOS devices which suffer from their inherent limitations such as high leakage current and limited sub-threshold swing of 60 mV/dec at room temperature [3, 4]. Owing to its mechanical degree of freedom in switching mechanism, NEM contact switches can attain the ideal switching characteristics in terms of steep sub-threshold swing, quasi-zero off-state leakage current, thermally independent switching and ultra-low power consumption [5–9]. Furthermore, they exhibit minimal degradation in the performance even in the harsh environments, such as high radiation fields, high temperatures and in the external electric fields [10–12]. Because of its excellent device performance, NEM contact switches can be suitable for new era of CMOS applications. However, NEM contact switches generally suffer from two main parameters, high pull-in voltage due to the limitations in the scalability of conventional three-dimensional (3D) bulk materials and lack of switching reliability due to contact surface degradation caused by repeatable physical contact in mechanical switching [13, 14]. The contact degradation leads to several forms of damages including wear, fraction, creep, electromigration, delamination and permanent stiction [15–17]. Lately, a vast range of new methods and materials in the structural designs of NEM contact switches have been implemented to improve their pull-in voltage and contact lifetime [18–20]. For example, mechanical switches based on the silicon carbide and ruthenium has shown improved switching cycles [21, 22].

On the other hand, newly emerging nano materials, including carbon nano tubes (CNT) [23], nano wires [24], transition-metal dichalcogenides [25] and graphene [26] have been studied to improve the performance of the NEM contact switches. Among the various nano materials proposed, graphene, an atomic layer of carbon atoms tightly arranged into a two-dimensional honeycomb lattice, promises an encouraging role in the field of NEM contact switches [27]. Attributes of the graphene such as excellent electrical and mechanical property with high Young’s modulus and tensile strength, exceptionally high electrical and thermal conductivities makes it as a suitable material for ideal NEM contact switch [28–30]. In addition, various carbon-based nano materials are also employed as the contact material to improve the contact lifetime of the NEM contact switch. For instance, the suspended CNT beam with diamond-like carbon as contact [31], vertically aligned CNTs with CNT as contact layer [32], multilayer graphene with multilayer graphene as contact [33], nano crystalline graphene (NGC) with NGC as contact material [34] and graphite-to-graphite contact [35], have been studied earlier for electromechanical contact devices, inertial switches [32] and charge transfer based gas sensor applications [36]. However, this new generation materials based NEM contact switches were also failed to offer a high contact lifetime due to contact degradation. Furthermore, the graphene based NEM contact switches failed to offer a long contact lifetime-an essential parameter for reliable NEM contact switches due to the irreversible stiction. Jian et al. reported that graphene-based two terminal NEM contact switch fabricated with gold (Au) as the contact material and achieved a low pull-in voltage of $< 2 \text{V}$ [37]. Nevertheless, the device performance was limited to few switch-
FIG. 1. The fabrication processes of self-aligned graphene covered actuation electrode-graphene NEM switches. (a) Schematic illustration of the G-G NEM contact switch. (b) Optical image illustrates the large scale array of the fabricated devices on Si/SiO$_2$ substrate (Scale bar is 200 $\mu$m). (c) Optical image taken after the transferring the contact graphene layer (Scale bar is 50 $\mu$m). (d) Raman spectroscopy of the transferred graphene layer. (e) The atomic force microscope (AFM) image of the device in (b) taken after sacrificial SiO$_2$ of 30 nm fabrication. (f) Height profiles measured for various samples with different SiO$_2$ thickness. The blue line corresponds to the measurement along the blue line in (e). (g) The tilted view ($\sim 45^\circ$) of the scanning electron microscope (SEM) image showing the double-clamped graphene beam of length of 1 $\mu$m and width of 0.5 $\mu$m (Scale bar is 0.5 $\mu$m).

Graphene was used as the contact material in graphene-based NEM contact switch to avoid the permanent stiction. Van et al. reported a three terminal graphene NEM contact switch with graphene as the contact material but the switch failed within few cycles due to poor geometrical design of the device [40]. Moreover, the switch was reported with high pull-in voltage of $> 7$
TABLE I. The geometrical dimensions and the electrical characteristics of the G-G NEM contact switches.

| Switch id | Geometrical Dimensions | Electrical Parameters |
|-----------|-------------------------|-----------------------|
|           | Length (µm) | Width (µm) | Airgap (nm) | Pull-in (V) | Pull-out (V) | On/Off ratio | Hysteresis (V) | Failure Type |
| S1        | 1           | 0.5        | 30          | 0.45       | 0.4         | 10^9        | 0.1          | S1tiction    |
| S2        | 2           | 0.5        | 60          | 1.1        | 0.9         | 10^9        | 0.2          | S1tiction    |
| S3        | 1.5         | 1          | 90          | 2.0        | 1.4         | 10^8        | 0.6          | Rolled-up    |
| S4        | 1.5         | 0.5        | 90          | 1.9        | 1.4         | 10^8        | 0.5          | Rolled-up    |
| S5        | 2           | 0.5        | 90          | 1.6        | 1.2         | 10^8        | 0.4          | Rolled-up    |
| S6        | 1.5         | 0.5        | 90          | 2.1        | 1.5         | 10^8        | 0.6          | Rolled-up    |
| S7        | 2           | 0.5        | 60          | 1.4        | 0.6         | 10^9        | 0.2          | Broken       |

V. Graphene was successfully utilized as a contact material in nickel based micro-electromechanical switches with long contact lifetime but failed to scale down the pull-in voltage [41]. As a result of the inability to reduce the thickness of the suspended Ni beam, the reported pull-in voltage is > 70 V.

In this paper, we report the experimental demonstration of a graphene-based two terminal NEM contact switches with ultra-low pull-in voltage suitable for new era of energy efficient low-power CMOS applications. The NEM contact switches were fabricated using the chemical vapor deposition (CVD) grown graphene as suspended beam as well as the contact material and referred as G-G NEM contact switches. The irreversible stiction was suppressed by utilizing the weak van der Waals (vdW) interaction between the suspended graphene beam and the contact graphene layer. The two terminal G-G NEM contact switches exhibit superior switching characteristics with a ultra-low pull-in voltage of ~ 0.45 V, sub threshold slope as small as < 10 mV/dec, stable pull-out at 0.4 V, high on/off ratio of ~ 10^9 and a small hysteresis window of < 0.1 V.

2. Experimental

2.1 Fabrication of G-G NEM contact switches

The Fig.1a shows the schematic illustration of the G-G NEM contact switches. The suspended graphene beam was used as the active element of the NEM contact switch and graphene covered top actuation electrode was used as the fixed element. The extended zoom-in view in Fig.1a illustrates the graphene covered top actuation electrode. The extensive fabrication process is given in the supplementary section-I & II of the manuscript. The Fig.1b demonstrates the large scale array of the fabricated devices on Si/SiO\textsubscript{2} substrate with dimensions (Length × Width) of 10×10 mm. Here, we also have used the CVD grown graphene as contact material. By exploiting the weak van der Waals interaction between the graphene layers, long endurance highly reliable NEM contact switches were achieved. The detailed contact mechanics between the graphene-to-graphene layers are published in the Ref. [42]. The Fig.1c shows the optical image of a device after transferred the contact graphene layer. The contact graphene layer was transferred on top of the fabricated sample using wet chemical based transfer method. (Refer supplementary section-III for more information on graphene transfer method). The Raman spectroscopy with Laser (HeNe) excitation source (λ= 532 nm) was employed to verify the existence of the contact graphene layer after the transfer. (See supplementary section-IV for more on Raman analysis of the transferred graphene layer). The Raman spectroscopy of the transferred contact graphene layer is shown in Fig.1d. The D peak observed at 1350 cm\textsuperscript{-1} indicates the existence of the lattice defects in the CVD grown graphene [43]. The G and 2D peaks were observed at 1580.5 cm\textsuperscript{-1} and 2680.4 cm\textsuperscript{-1}, respectively. This demonstrates the single layer graphene with weak built strain after transferring the graphene on SiO\textsubscript{2} surface [44].

The G-G NEM contact switches were fabricated with three different air gap thickness of 30 nm, 60 nm, and 90 nm, respectively. This is achieved by varying the thickness of the sacrificial SiO\textsubscript{2} thickness. (See supplementary section-V for more on AFM analysis of the thickness of sacrificial SiO\textsubscript{2} layer). The Fig.1e shows the AFM image of the device taken after the sacrificial SiO\textsubscript{2} deposition of 30 nm. The line profiles obtained for the various thicknesses from AFM results are furnished in Fig.1f. The Fig.1g shows the tilted view of the SEM image obtained for a device (S1) after the electrical measurement.

2.2 Electrical measurement configuration of G-G NEM contact switches

All the electrical measurements were carried out using semiconductor device analyzer (Keithley–4200 SCS) with measure resolution of ~ 10 aA. To avoid the moisture related failures of the switches, the measurement chamber was vacuumed to ~ 10\textsuperscript{-4} Pa. To confirm the conductivity of the suspended graphene beam, the drain current (Id) across the graphene beam was measured as a function of the applied drain voltage (Vd). To investigate the mechanical switching characteristics of the device, the two-point probe method was used. Subsequently, the measurements were carried out in the following order: 1) high-resolution sweeps by ramping the applied voltage (Va) with step size of 7 mV and monitoring the switching current (Is). 2) low-resolution fast-cycling measurements. During the low-resolution measurements, the applied bias voltage (Va) of 0.5 V
FIG. 2. High-resolution mechanical switching characteristics of G-G NEM contact switch. (a) I–V responses measured between the anchor electrode to top actuation electrode and anchor-to-anchor electrodes. (b) Measured switching current (I_s) as a function of the applied voltage (V_a). (c) Repeatable switching measurements of the switching current (I_s) as a function of the applied voltage (V_a) for 30 switching cycles. (d) Measurement of the switching current (I_s) for the different applied voltage pulses as a function of time. (e) The enlarged switching transition (pull-in) from off-state to on-state and (f) switching transition (pull-out) from on-state to off-state of G-G NEM switch in (b) with curves fitted by the linear function.

was applied and the current was continually monitored with a compliance limit of 5 µA for on-state and voltage of 10 mV was applied to measure the current at off-state. All the measurements were carried out in vacuum at room temperature. In total, seven devices of G-G NEM contact switches were presented and all devices shown qualitatively similar switching behaviors except the failure modes. The Table I lists the designed geometrical dimensions as well as the observed electrical characteristics of the devices. We present the electrical measurement results obtained from the device S1, unless otherwise noted.
3. Results and Discussion

3.1 Electrical characterization of G-G NEM contact switches

The Fig. 2 shows the switching characteristics of the G-G NEM contact switch S1. The current-voltage (I-V) responses measured between the anchor to anchor electrodes and anchor to top actuation electrode before mechanical switching operation is shown in the Fig. 2a. It can be seen from Fig. 2a, the suspended beam and the top actuation electrode were isolated electrically. The two point probe based switching measurement was conducted between the suspended graphene beam and graphene covered top actuation electrode as shown in Fig. 1a. The measured switching current (I) with respect to the applied voltage (V) with current compliance of 5 µA in vacuum is shown in Fig. 2b. During the forward sweep of the applied voltage V, the contact between the graphene beam and the contact graphene (Gr/Au) occurred at 0.45 V (pull-in voltage) and the measured switching current is increased abruptly to the compliance value of 5 µA from very low off-state current floor of < 100 fA. At pull-in the suspended graphene beam made a contact with contact graphene/Au top actuation electrode. The region of the contact area increases as the applied voltage is increased, which in turn reduces the contact resistance. During the reverse sweep, the switching current instantly falls in to off-state current floor (completely turned off) at the applied voltage of 0.4 V (pull-out voltage). It is worth to mention that, at pull-out, on-state to off-state transition occurred in a single sweep voltage step of 7 mV. The measured hysteresis window of the switch is < 0.1 V. For the first thirty switching cycles, the deflection in the pull-in voltage is significantly very minimum of < 10 mV as illustrated in the Fig. 2c. To verify the steep and stable switching behavior, the switching current (I) is measured for voltage steps with different values. The switching characteristics for applied voltage pulses as a function of time are shown in the Fig. 2d. It is observed that the current (I) is only reached the compliance value for voltages higher than the pull-in voltage, for any values of Va less than pull-in voltage the switching current (I) is remains in the off-state. This measurement is useful for detecting the deviation in pull-in and pull-out voltages and reveals the stability of a switch. The linear fit of switching slopes of the pull-in and pull-out transition is illustrated in Fig. 2e and Fig. 2f, respectively. The steep switching slope (SS) for the first switching cycle from the I-Va curves were determined as <10 mV/dec for the pull-in (SS pull-in) and <10 mV/dec for pull-out (SS pull-out). The respective on/off ratio of the switching current is ~ 10^9 orders of magnitude, which is higher than those of previously reported studies on graphene-based NEM contact switches [34, 37, 38, 40]. (See supplementary section-VI for more information on electrical failure analysis of G-G NEM contact switch).

The effect of the graphene layer at the contact interface is well evident from the switching characteristics of G-G NEM contact switch. Especially, the sharp transition in the pull-out curve is direct evidence of the reduced contact adhesion between suspended graphene beam and top actuation electrode. During the mechanical switching operations (on/off transitions) the contact graphene plays an important role. The contact graphene significantly reduces the physico-chemical degradation at the contacting interface owing to its stable mechanical and chemical properties of the graphene [45]. The exceptionally small variation in the pull-out voltage (∼ 10 mV) is obvious evidence for the well-controlled stiction at the graphene-to-graphene contact interface. Unlike the GNEM switches reported earlier, which failed to perform mechanically, the G-G NEM contact switches demonstrated with stable and sharp pull-in and pull-out switching slopes over numerous switching cycles. The result indicates that the G-G NEM contact switches were stiction free, and stiction was surpassed by the weak van der Waals interaction at the graphene-to-graphene contact. The switching behavior of GNEM switches with gold (Au/Cr_2O_3) as contact material was given in the supplementary section VII for comparison. However, the control device (Au/Cr_2O_3) was failed within few switching cycles. The failure is mainly due to chemical bond formation between the carbon and gold atoms [46].

3.2. Long-Term Contact Lifetime Measurements

The low resolution hot-switching experiment is carried out to verify the contact lifetime of G-G NEM contact switch as well as the current carrying capabilities of graphene as a contact material. The deformability and low adhesion of the double-clamped graphene beam on the contact graphene were also investigated during the long-term contact switching operation. In this measurement, the switch was placed under continuous mechanical stress especially on the contact region of switch. These rapid cycling measurements also divulged the failure mechanism associated to the mechanical wear of the contact surfaces. Barring mechanical wear, other contact failure mechanisms such as surface oxidation or contamination can also occur during storage [47]. The contact reliability of G-G NEM contact switch was obtained as an outcome of the hot-switching measurements.

The Fig. 3a illustrates the long-term contact lifetime measurements showing on-state and off-state switching current for each cycle. The electrical measurements were performed by applying static voltage between the suspended graphene beam and actuation electrode, defined as hot switching condition, with bias voltage of 0.5 V for on-state with current compliance limit of 5 µA and 10 mV for off-state. The switch continued to cycle with a stable on-state current of 5 µA for more than 1.5 million switching cycles and did not suffer mechanical failure. It can be seen from Fig. 3a that the on-state current of 5 µA was reached for all switching cycles (> 1.5 million) without any significant reduction in on-state current. On the other hand, the off-state current was gradually increased
Fig. 3. Long-term hot switching characteristics of G-G NEM contact switches. (a) On-state and off-state switching current \( I_s \) of switch S1 for \( > 1.5 \) million switching cycles. (b) On-state and off-state switching current \( I_s \) of switch S2 for \( > 5 \) million switching cycles. Switching current compliance limit was set to 5 \( \mu \)A for (a-b). (c) Failure of the switch S1 during the inter-spread high resolution switching measurement after 1.5 million switching cycles. (d) Failure of the switch S2 during the hot-switching measurement itself. The +5m annotation on the x-axis of (d) indicates the switching cycles measured after the 5 millions of switching. (e) The Radar plot of various types of failures observed in the G-G NEM contact switches for 30 nm, 60 nm and 90 nm. (f) Relationship between the pull-in voltage and failure by stiction plotted against airgap thickness.

From \( \sim 10 \) fA to \( \sim 1 \) pA as switching cycles increase. The Fig.3b illustrates the long-term endurance of the switch S2 with \( \sim 5 \) millions of switching cycles. It is well evident that each switch exhibits different contact life time over its switching course and it varies for each device. The common traits observed among all the measured devices was that on-state current remains stable throughout the long-term measurement and the off-state current gradually increases over the time of switching operation. Additionally, more than \( 10^2-10^4 \) orders of magnitude change in the off-state current was observed in all the measured devices. The change in the off-state current was illustrated in three different regions in the Fig.3b. In all the measured switches, the electrical migration or
welding caused by the Joule heating was not observed. The change in the off-state current is attributed to the structural changes in the suspended graphene beam due to dynamic and continuous switching. Fig.3c illustrates the failure of the switch S1 while conducting the inter-spread high-resolution switching measurement. One possible reason could be changing the measurement speed from 100 msec per switching cycle (complete pull-in and pull-out operation) to 100 sec to reach the pull-in. It is worth noting that, during the low-resolution hot switching measurements itself the graphene at contact has been started to extinct, which is explained further in section 3.3. The slow speed inter-spread high-resolution measurement makes the suspended graphene vulnerable to being stuck into the top-actuation electrode. Fig.3d illustrates the failure of the switch S2 during the hot-switching measurements itself. After more than five millions of switching cycles the switch continues to work at stable off-current for few hundreds of switching cycles. Then, off-current linearly increases from the off-state current floor of ~ 1 nA to compliance limit of 5 µA with in 100 switching cycles and got stuck with the on-state current level owing to stiction. (See supplementary section-VIII for more information on reproducibility of switching behaviours of G-G NEM contact switch).

The radar plot in Fig.3e illustrates the various types of failures observed in G-G NEM contact switches. A total of 192 devices were considered for this analysis with 64 devices each for 30 nm, 60 nm and 90 nm air gap thicknesses, respectively. A significant portion of all the fabricated devices were failed prior to the electrical measurement. The pre-electrical failures including writing errors in electron beam lithography (EBL) process, overlapping of electrodes due to the misalignment of exposed patterns in EBL and the broken electrodes/contact pads during the fabrication process. (Refer the supplementary section-IX for more on the pre-electrical measurement failures in the G-G NEM contact switches). Stiction, rolled-up graphene beam, and broken graphene beam are three different types of failures observed post-electrically. Stiction constitutes more than one third (~ 35 %) of failures in all fabricated devices. This is attributed to the degradation of the contact graphene during the long-term continuous hot-switching measurements. It is also worth to mention that the failure by stiction is very high (~ 50%) for the devices fabricated with small air gap thickness (30 nm). Fig.3f illustrates the rate of failure by stiction over different air gap thickness. It is well evident from the figure that the small air gap thickness significantly reduces the pull-in voltage, but the rate of failure by stiction is increased with the decrease in the air gap thickness. Even though the air gap thickness was set well above the active range of van der Waals force [48], increased rate of stiction at 30 nm was attributed to buckling of graphene beam. In addition, the broken graphene beam during the electrical measurement causes another 25% of the failures observed. It can be important to note that, the broken graphene beam is either caused during the fabrication process itself or during the electrical measurement.

### 3.3. Various types of failures in G-G NEM contact switches

To understand the failure modes in the fabricated switches, we examine the SEM image of devices after the electrical measurement. We consider six different switches and their geometrical dimensions as well as the electrical performance are furnished in the Table I. The Fig.4 illustrates the SEM images of G-G NEM contact switches with various types of failures. The Fig.4a - Fig.4f corresponds to the switches of S2 - S7 in Table I, respectively. Stiction is one of the common failure modes in the G-G NEM contact switches; the suspended graphene beam is stuck on to the fixed top actuation electrode and keeps the switch closed even after the applied electrical voltage is completely removed. As mentioned earlier, the adhesive forces at the contact interface are greatly reduced owing to the van der Waals interaction between the graphene-to-graphene contact. However, we found that three different types of failure modes in the fabricated G-G NEM contact switches.

The Fig.4a shows the SEM micrograph of a failed device, the graphene beam is stuck on to the actuation electrode. The geometrical dimensions of the device obviously remain undamaged after the electrical measurement. However, in a closer look one can observe that the suspended graphene beam has many defect sites. As we have used CVD grown graphene, it is assumed that the defects were present in the graphene beam even before the electrical measurement [49]. More likely, the continuous mechanical switching may increase the defects in graphene beam and subsequently reduces mechanical stability of the switch. We attribute a similar scenario at the contact graphene for the device failure. The failure of the switch with graphene as contact layer in vacuum was owing to irreversible stiction after extinction of contact graphene at the contact site of the top actuation electrode. The single layer CVD grown graphene was used as the contact layer, the CVD graphene has point and line defects [50]. The continuous mechanical switching with very high speed at such a defect site may eventually lead to more defects and subsequent extinction of graphene layer at the contact [51]. After the extinction of graphene at the contact, the suspended graphene directly makes contact with metal electrode. This may lead to permanent stiction of suspended graphene beam on to the metal electrode. The Fig.4b represents a similar failure of the device with infinitesimal structural damage and changes were observed in the graphene beam. The failure of the device is due to stiction of the graphene beam which might have been caused by extinction of graphene at the contact site.

The Fig.4c represents a device failure with significant observable changes in the geometrical dimensions. The edges of the suspended graphene beam start to roll-up and remain unaffected at the anchor electrodes. The red
FIG. 4. Various types of failure modes observed in G-G NEM contact switches. (a) Stiction of graphene beam with the top actuation electrode. (b) Stiction of suspended graphene beam with significant geometrical changes in the graphene beam. (c) SEM micrograph of a device with rolling-up of the suspended graphene along the edges. The red dotted lines represent the originally designed width of the graphene beam; the arrows indicate the structural damage caused by rolling-up of graphene beam. (d) Completely rolled-up graphene beam. (e) A semi broken suspended graphene beam at the anchors. (f) Failure caused by fracture of the suspended graphene beam at the anchor. The scale bar is 0.5 µm and it is common for (a-f).

dotted lines in Fig.4c represent the originally designed width of the graphene beam; the arrows indicate the structural damage caused by rolling-up of graphene beam. The Fig.4d represents a device failure with completely rolled-up graphene beam. The Fig.4e illustrates a device failure with completely rolled-up graphene beam and almost broken at one end of the anchor. In addition, long suspended side of the graphene beam with respect to actuation electrode rolled-up more than the shorter side. Owing to reduced restoring force at the anchors of long suspended side of the graphene beam, it deteriorates more and the damages are significant which is consistent with the classical theory of micro beams [52]. Another common failure mode is, broken suspended graphene beam as shown in the Fig.4f. Breaking mainly occurred at anchoring ends of the graphene beam owing to under etching of the SiO$_2$ at the anchoring electrodes. Under etching is caused by the buffered hydrofluoric acid (BHF) based isotropic wet chemical etching method [53]. It is also worth to note that, most of the fractures in the graphene beam were observed at the long suspended side. Asymmetry in the suspended graphene beam with respect to top actuation electrode is unintentional and it was caused by the misalignment in electron beam exposure during the fabrication process. Owing to the repeated mechanical switching, the mechanical stability of graphene beam is reduced and the edges started to roll-up. The rolling leads to the reduction in contact area of the switch. The increase in contact resistance can be attributed to reduced width of the suspended graphene beam. The relationship between asymmetric electric field and mechanical stability will be further investigated in the following section.

3.4. Variations in the pull-in voltage of G-G NEM contact switches with identical device dimensions

One of the very important aspect of transistors in the CMOS electronics is that it’s stable threshold or on-state voltage [54]. The on-state voltage or pull-in voltage in the NEM contact switch is highly depends on the geometrical dimensions of the switch. So it is essential to discuss the fabrication degree of merits that influences the pull-in voltage in the G-G NEM contact switch. We have observed variations in pull-in voltage of the G-G NEM contact switches with identical device dimensions. To understand the reason behind this phenomenon, we have fabricated G-G NEM contact switches with systematic intentional shift of the top actuation electrode with respect to the suspended graphene beam. (See supplementary section-X for more on pull-in voltage variation). The SEM micrographs of the devices are shown from the Fig.5. The SEM images were taken after the electrical measurement. All the switches are fabricated with identical geometrical dimensions of length of 1 µm, width of 0.5 µm and air
FIG. 5. Misalignment induced pull-in voltage variation in G-G NEM contact switches. (a-e) The top actuation electrode shift of the G-G NEM contact switches with respect to suspended graphene beam after 0 nm, 50 nm, 100 nm, 150 nm, and 200 nm, respectively. The scale bar is 0.5 \( \mu \)m and it is common for (a-e). (f) Variation in the pull-in voltage (VPI) with respect to shift of the top actuation electrode.

Gap thickness of 60 nm. From the SEM micrographs, it is evident that the top actuation electrodes of the switches were shifted towards the right anchor electrode with respect to center of the graphene beam. The narrowing of the gap between top actuation electrode and anchor electrode is clearly visible in the Fig.5a to Fig.5e. The systematic shift of the top actuation electrode induces the asymmetry in the device structure. This asymmetry induces the asymmetric electric field between actuation electrode and suspended graphene beam. The electric field strength at the center of the graphene is linearly decreases with respect to the shift of the actuation electrode.

In other words, the switches with large shifted top actuation electrode need more voltage to deform the suspended graphene beam for same air-gap thickness compared to switches with no shift in the top actuation electrode.

### 3.5. Finite Element Method simulation of G-G NEM contact switches

In order to understand the manifestations of the mechanical failure modes owing to the asymmetric electric field generated by the misalignment of top actuation electrode, a 3D FEM based simulation of the G-G NEM contact switch was conducted by replicating the experimental device structure. The electrical and mechanical characteristics of the G-G NEM contact switch were simulated using the FEM based tool COMSOL (5.6, COMSOL Inc., Burlington, MA, USA) [55]. (See Methods for more details on FEM modeling). Furthermore, to reduce computational complexity the geometrical dimensions of device S2 is adopted for FEM simulations. The Fig.6a shows initial structure of the simulated G-G NEM contact switch in COMSOL simulation environment with meshing nodes. To understand the mechanical properties owing to the asymmetric electric field, two different structures were studied. The schematic diagrams of the structures are illustrated in the Fig.6b. In the first case, the center of the top actuation electrode is aligned well with the center of the graphene beam, referred as the C-C...
FIG. 6. FEM simulation of the G-G NEM contact switches. (a) Initial structure of the G-G NEM contact switch with tetrahedral meshing. Each material layer is color coded with unique colors, red, magenta, blue and yellow respectively for Si, SiO$_2$, graphene and gold. (b) Schematic illustration of C-C and C-E structures. (c) 1-D line plot of the beam displacement. (d) The 3D profile of the double-clamped graphene beam displacement at 1.3 V; Color legend shows the displacement in meter. (e) The potential distribution (3D) of the switch across the center of the graphene beam; Arrows illustrate the electric field direction; Color legend shows the potential in volt. (f) The 1D line plot of the principal stress (tensile) for C-C aligned and C-E misaligned structures. (g) The 1D line plot of the electric filed strength for C-C and C-E structures.

(center-to-center) aligned structure. In the second case, center of top actuation electrode is shifted with respect to center of the graphene beam. This was done purposefully to replicate the experimental device with misalignment, and referred as the C-E (center-to-edge) misaligned structure. This shift creates asymmetric mechanical behavior of graphene beam with respect to center aligned device structure. The graphene beam was modeled as a linear isotropic material with a thickness of 0.35 nm. The initial air gap thickness between the suspended graphene beam and the actuation electrode was set to 90 nm, with a length and width of the beam of 2 µm and 0.5 µm, respectively. The model was meshed with a global tetrahedral mesh with minimum element size of 0.35 nm was adopted to refine the mechanical deformation of the suspended graphene beam precisely. In addition, to obtain the accurate stress gradients along with the deflected graphene beam, the graphene beam has meshed with swift mesh. (Refer supplementary section-XI for more information on FEM analysis of the NEM contact switch).
For graphene the mechanical properties such as, density of 2.2 g cm\(^{-3}\), Young’s modulus of 1 TPa, and Poisson’s ratio of 0.17 were used [56]. In this FEM model, the out of plane mechanical properties of the graphene beam is considered only within the limits of linear elastic theory [29]. First, the pull-in was confirmed by beam displacement. Fig. 6c illustrates the beam displacement of 90 nm for 1.3 V, which is the complete air-gap closing distance by graphene beam. The pull-in voltage obtained in FEM simulation was closely resembles to the experimental result. The Fig. 6d illustrates the beam displacement in 3D at pull-in voltage for C-C aligned structure. The potential distribution of the switch across the center of the graphene beam is illustrated in Fig. 6e and arrows represents the electric field direction. The tensile stress was analyzed further to understand the failure modes. The 1D line plot of the stress along the graphene beam is shown in the Fig.6f. The tensile stress profile of the deflected graphene beam at the pull-in voltage for center aligned and misaligned structure with 400 nm is shown in Fig. 6f. It is well known from the figure that center aligned structure has very symmetric stress profile and the misaligned structure has very asymmetric stress profile. The stress reaches the maximum value at pull-in condition. The tensile stress profile was very symmetry with respect to the center of the graphene beam for C-C aligned structure and the maximum value is \(~30\) GPa. The asymmetric stress behavior was obtained for misaligned structure. Furthermore, tensile stress reached the maximum value \(~60\) GPa, which is comparable to breaking strength of the CVD graphene reported in the literature [57]. During the continuous mechanical switching of the device, the asymmetric and high magnitude stress in the suspended graphene beam can facilitates the rolling-up of the graphene beam and subsequently leads to fracture of the graphene beam. The Fig.6g shows the electric field strength for both C-C structure as well as C-E misalignment structure. The 1D line profile data for electric field strength was obtained from the spatially generated 3D cut line set \(\sim5\) nm above the suspended graphene beam. The electric field reaches the maximum value at the edges of the graphene beam for both of the cases but evidently the magnitude of the electric field is reduced for the misaligned case. To understand further, we consider the single point integration of the electric field strength at the midpoint of the graphene beam.

The Fig.5f shows the electric field strength in FEM, and the pull-in voltage obtained experimentally as function of the misalignment. It is obvious that the electric field strength at midpoint of the graphene beam reduces as the misalignment increases; this is consistent with the increased pull-in voltage of the device. The FEM analysis of the G-G NEM switches with misalignment of the top actuation electrode reveals that the asymmetric electric field around the graphene beam can be one of the plausible reasons for the observed pull-in voltage deviation in the G-G NEM contact switches with identical device dimensions. The two terminal graphene NEM contact switches designed with graphene as contact material can possibly utilized as an alternative for the conventional CMOS transistor. Furthermore, the low pull-in voltage with very high contact lifetime endurance has always been expected of NEM contact switches and the G-G NEM contact switches are reported with better switching performance in terms of low pull-in voltage and high reliability compared to the NEM switches reported in the literature (Refer supplementary section-XII for more information on literature review of the high reliable NEM contact switches). Our device can be potentially used for energy efficient era of ultralow-power CMOS and CMOS-NEM hybrid integrated circuits.

4. Conclusion
We developed an electro-statically enabled graphene based NEM contact switch with graphene as the contact material. The fabricated G-G NEM contact switches demonstrated with an ultra low pull-in voltage of \(<0.5\) V as well as high contact lifetime of \(>1.5\) million switching cycles. The switches also showed an excellent switching performance, includes low off-state leakage current, stable on-state current and high on/off ratio. The G-G NEM contact switches demonstrated with stable electrical contact and maintained with an on-state current of \(5\) \(\mu\)A for more than five million switching cycles. Various types of failures that occurred in the G-G NEM contact switches were quantitatively analyzed. The role of an asymmetric electric field in the switching characteristics was also investigated in detail. The work presented here demonstrates that G-G NEM contact switch can be a potential candidate for achieving a reliable ultra-low power energy efficient switching applications.

Methods
G-G NEM contact switch fabrication: First, the CVD grown graphene on Si/SiO\(_2\) surface is used as the substrate (See supplementary section-I & II for the detailed fabrication processes). Then graphene ribbon is fabricated by using the positive resist poly (methylmethacrylate) (PMMA), and then the pattern was defined by electron beam lithography (EBL) exposure. The unwanted graphene is removed using oxygen plasma based dry etching. The anchor metal electrode is fabricated using the positive bi-layer resist of PMMA/methylmethacrylate (MMA) and the metal electrode (Cr: Au :: 5:85 nm) was deposited by using electron beam (EB) evaporation. The sacrificial SiO\(_2\) is fabricated using PMMA/MMA bi-layer resist followed by EBL pattern and SiO\(_2\) was deposited using EB evaporation. After fabricating the sacrificial SiO\(_2\) layer, another layer of CVD graphene was transferred onto the sample using a wet chemical based transfer method (see supplementary section-III for more details on graphene transfer process). The transferred graphene
layer is patterned using the PMMA, and the unwanted graphene was removed using oxygen plasma etching. The top actuation electrode was fabricated using the PMMA/MMA bi-layer resist, the metal electrode (Cr/Au: 5/85 nm) was deposited by using electron beam (EB) evaporation. Unwanted graphene remaining on the sample was removed by using oxygen plasma etching. The transferred CVD graphene layer bonds with Cr metal layer. The bonding between out-of-plane dangling C atoms in the graphene layer and metal atoms leads to a strong Cr-C bond. The transferred graphene layer act as an anti-stiction coating to reduce the mechanical failures related to the surface adhesion and other reliability issues. Finally, the sacrificial layer (SiO$_2$) between the bottom GNR and the top actuation electrode was etched in buffered hydrofluoric acid (1:5) and dried in super-critical point dryer. This process leads to suspension of GNR from bottom SiO$_2$ and air-gap between the suspended GNR and the actuation electrode.

**Mechanical performance calculation:** The mechanical restoring force of a doubly clamped GNR can be calculated theoretically using the following equation [52].

\[
\{ F_{\text{restoring}} = -Kd \} \tag{1}
\]

\[
\begin{align*}
K &= 59.52EW \frac{t^3}{L^3} \tag{2} \\
F_{\text{vdw}} &= \frac{A_H A}{12\pi Z^2} \tag{3}
\end{align*}
\]

The van der Waals force between the two graphene layers can be calculated as

Where K is the spring constant of the doubly clamped beam, E is the Young’s modulus of the graphene, t, L, and W are the thickness of the single layer graphene of 0.35 nm, length and width of the suspended GNR, respectively. A is the contact area of the switch (0.25 $\mu$m$^2$) and A$_H$ is the Hamaker’s constant [58] of graphene taken to be 4.7 x 10$^{-19}$ J, Z is the interlayer distance between two graphene layers is taken to be 0.335 nm [59]. The mechanical restoring force of doubly clamped graphene beam of length of 1 $\mu$m and width of 0.5 $\mu$m is calculated as 39 pN, 77 pN and 115 pN for the air gap thickness of 30 nm, 60 nm and 90 nm, respectively. whereas vdW force between graphene-graphene interfaces is $\sim$28 fN.

**Finite Element Method (FEM) simulations:** In FEM simulations, COMSOL Multiphysics (5.6, COMSOL Inc., Burlington, MA, USA) package with MEMS module was used. MEMS module solves the electrostatic field with mechanical forces. In addition, MEMS module also allows to couple these fields and simultaneously map the beam deflection, electric field distribution, charge density around the beam, and stress profile of the NEM contact switches in 3D mode. The electrostatic field in the air and in the graphene beam is governed by Poisson’s equation $-\nabla \cdot (\epsilon \nabla V) = 0$. The bias potential is applied to the top actuation electrode and the suspended graphene beam is grounded. All the other boundaries in the model are electrically isolated. In this simulation, a 3D analysis is done by solving coupled electromechanical equations. The NEM contact switch model is made up of seven layers. All the seven layers are encapsulated with an additional layer which is modelled as air. The material properties were imported from COMSOL Multiphysics materials library except for graphene, which is cited from the literature. In order to numerically solve the coupled model by FEM, the whole device structure has meshed with a user defined mesh. The different element size was used for each layer. The average element quality of the mesh is about 0.7, where 1 is represented as an ideal and 0 is represented as degenerated mesh elements.

**A. Author contributions**

H.M. proposed the project. J.K conceived the experimental concept. J.K. performed the experimental work including, mask design, electron beam lithography, electron beam evaporation, reactive ion etching, wet chemical based graphene transfer process, electrical transport measurements and data analysis. J.K. was responsible for conducting all the FEM based simulations, and analysis of the FEM data. M.M provided the guidelines for fabrication process and manuscript writing. J.K. wrote the manuscript. M.M and H.M. supervised the project.

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**C. Data availability**

The original measurement data supporting the findings in this work are openly available in the Zenodo repository with the identifier ‘https://doi.org/10.5281/zenodo.6656591’
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Supplementary Information:
A Large Scale Fabrication of Graphene Based Nanoelectromechanical Contact Switches With Ultra-low Pull-in Voltage

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I. THE DETAILED FABRICATION PROCESS OF G-G NEM CONTACT SWITCH

Fig. S1 illustrates the fabrication process for graphene-graphene NEM contact switching devices.

- First, the CVD grown graphene on Si/SiO$_2$ surface was used as the substrate (Fig. S1a).
- The graphene ribbon was fabricated by using the positive resist poly (methylmethacrylate) (PMMA), and then the pattern was defined by electron beam lithography exposure.
- The graphene elsewhere was removed using oxygen plasma dry etching (Fig. S1b).
- The anchor metal electrode was fabricated using the positive bi-layer resist PMMA/MMA and the metal electrode (Cr/Au) was deposited by using electron beam (EB) evaporation. The total thickness of the metal electrodes was 5/85 nm (Fig. S1c).
- The sacrificial SiO$_2$ was fabricated bi-layer resist and SiO$_2$ was deposited using EB evaporation. The total thickness of the metal electrodes was $\sim 60$ nm (Fig. S1d).
- After fabricating the sacrificial SiO$_2$ layer, another layer of CVD grown graphene was transferred onto the sample using a wet chemical based transfer method (Fig. S1e). (See supplementary data for more on graphene transfer process).
- The transferred graphene layer was patterned using the PMMA, and removed remaining graphene using oxygen plasma etching (Fig. S1f).
- The top actuation electrode was fabricated using the PMMA/MMA bi-layer resist, the metal electrode (Cr/Au) was deposited by using electron beam (EB) evaporation (Fig. S1g). The total thickness of the metal electrodes was 5/85 nm.
- Unwanted graphene remaining on the sample was removed by using oxygen plasma etching (Fig. S1h). The transferred CVD graphene layer was bonded with Cr metal atoms. The bonding between out-of-plane dangling C atoms in the graphene layer and metal atoms leads to a strong Cr-C bond. The transferred graphene layer act as an anti-stiction coating to reduce the failures related to the surface adhesion.
- Finally, the sacrificial layer (SiO$_2$) between the bottom graphene ribbon and the top actuation electrode with contact graphene was etched in BHF (1:5) and dried in super-critical point dryer [1]. Thus, the removal of the SiO$_2$ between graphene layer and top actuation electrode leads to air-gap between the suspended graphene ribbon and the actuation electrode (Fig. S1h).
Fig S. 1 – The fabrication processes of self-aligned graphene covered actuation electrode-graphene NEM switches.
(a) CVD graphene on Si/SiO_{2} substrate. (b) Graphene ribbon fabrication. (c) Anchor electrode fabrication. (d) Sacrificial SiO_{2} layer fabrication. (e) Contact graphene transfer process. (f) Etching process of the transferred graphene. (g) Top actuation electrode fabrication. (h) Etching process remaining graphene. (i) Releasing of sacrificial SiO_{2} using the buffered hydrofluoric (BHF) acid.
II. FABRICATION PROCESS: AN OPTICAL IMAGE FLOW OF DEVICE FABRICATION

The fabrication process of G-G NEM contact switches are explained in the following steps: - The detailed optical image illustration of the fabrication process is illustrated in Fig.S2

- Chemical Vapor Deposition (CVD) grown graphene on the SiO$_2$/Si was used as the substrate.
- Pre-pattern Au/Cr mark (85/5 nm) on SiO$_2$/Si substrate for e-beam lithography (EBL) alignment
- The graphene ribbon was patterned using PMMA, followed by deposition of metal electrodes Au/Cr (85/5 nm)
- Definition of 90 nm SiO$_2$ sacrificial layer
- Transfer contact graphene on top of the SiO$_2$ sacrificial layer
- Pattern contact graphene by EBL then etching by oxygen plasma
- Pattern and deposition top actuation Au/Cr (85/5 nm) electrodes.
- Releasing drain graphene in BHF followed by supercritical point drying using CO$_2$ as carrier gas.

![Fabrication process steps](image-url)
III. A WET CHEMICAL BASED GRAPHENE TRANSFER PROCESS

We used the CVD grown graphene as the contact material. In order to transfer the CVD grown single layer graphene from the copper (Cu) foil on to the device substrate, first, one side of the Cu foil was spin coated with poly (methylmethacrylate) (PMMA). The spin coated Cu foil was baked at 85 °C for 3 min. The graphene on the other-side of Cu foil was removed with an O₂ plasma etch. The stack of Cu/graphene/PMMA was then placed in a FeCl₃-based copper etchant (0.1M concentration) for ~ 10 hrs, which allows the copper to dissolve. The remaining graphene/PMMA film was rinsed in DI water for several times. After rinsing, the graphene/PMMA film was transferred on to the device structure. After transfer, first, the device substrate was naturally dried, and then it was baked at 75 °C for 30 min. The PMMA on top of the device was removed using acetone boiling (60 °C for 30 min) followed by the rinse with Isopropyl alcohol (IPA). Then the sample was dried again naturally for ~ 2 hrs.
In order to confirm the existence of the graphene layer after transfer to the sample, we have conducted the Raman spectroscopy. The Raman spectra in this study were obtained using a Horiba Raman spectrometer (T64000) with a solid-state crystal laser ($\lambda = 532 \text{ nm}$) as the excitation source. The sample was focused with a 100x objective lens along with a digital zoom option for precisely locating the specific spot in the sample. The laser power of 5 mW was used. The area of the laser beam spot was optimized to $\sim 1 \mu m^2$ by using optical lenses. The Fig.S3a shows the optical image of the device after the graphene layer was transferred. We have collected Raman spectra for three different locations in the sample, as marked with different colors in the image (optical). The corresponding Raman spectroscopic results are shown in Fig. S3b. The orange, red, and blue spots represent Raman spectra of the graphene respectively for on substrate SiO$_2$, on deposited SiO$_2$ and on gold. In all the locations we have obtained the clear Raman spectra, which indicates the clear existence of the transferred graphene (contact graphene) on the fabricated device. The Fig.S3c illustrates the G peak of the Raman spectra obtained for all three different spots. The Fig.S3d illustrates Double resonance (2D) band of the Raman spectra. The small enhancement in the intensity was observed in both 2D band as well as the G band for graphene on gold, which is in good agreement with the published result [2]. There is no significant change was for graphene on the deposited SiO$_2$. In addition, there is no fracture in the transferred graphene layer was observed in the sample.

Fig S. 3 – The Raman spectroscopy analysis of transferred graphene layer. (a) Schematic illustration of the transferred graphene layer on the fabricated sample. (b) Raman spectra were taken from the three different spots on the sample as marked in the schematic illustration. (c) The enlarged G band region of the transferred graphene with small enhancement in intensity. (d) The enlarged Double resonance (2D) peak of Raman spectra show the slight enhancement of the intensity with no frequency shift of the 2D band for graphene on gold pads.
The additional information on the atomic force microscope (AFM) data is included in this section. The AFM image of device after the sacrificial SiO$_2$ deposition is shown in Fig.S4a. The 1D line profile measured along the red line in Fig.S4a is shown in the Fig.S4b. The measured thickness of the deposited SiO$_2$ is $\sim 60$ nm. AFM image of a device with pre-electrical failure is shown in Fig.S4c. The top actuation electrode is overlapped with the anchor electrode. In addition, the AFM image of the device after the electrical measurement is shown in Fig.S4d. It can be seen from the figure that the suspended graphene beam is got stuck on the top actuation electrode. Moreover, the one side of the graphene beam is also damaged significantly than the other side of the beam with respect to the actuation electrode. The damages caused by the continuous and repeated mechanical switching of the suspended graphene beam.

Fig S. 4 – Pre-electrical failure modes observed in G-G NEM contact switches. (a) AFM image of the device taken after sacrificial SiO$_2$ fabrication. (b) Height profiles measured for various samples. The measurement corresponds to the measurement along the red line in (a). (c) AFM image of a device with pre-electrical failure. (d) AFM image of a device with post-electrical failure.
VI. ANALYSIS OF ELECTRICAL FAILURE IN G-G NEM CONTACT SWITCHES

In this section, we present the electrical failure of the G-G NEM contact switch during the low resolution long term switching measurements. Fig.S5a shows the long-term switching measurements of the graphene-graphene NEM contact switch. The switching current (Ims) is plotted in terms of measurement time.

Interestingly the switch fails during measurement itself. Fig.S5a illustrates the Low-resolution switching measurements on-state and off-state switching current (Ims) for each cycle. Switching current compliance limit of 5 µA was reached for over few hundred switching cycles (∼ 225 switching cycles). At the 226th switching cycle the on-state current does not reach the compliance limit, the switching current suddenly drops to off-state and remains in the off-state floor for rest of the measurement time. Zoom-in view of the failure point is shown in Fig.S5b. To further understand the device failure the SEM image was taken after the electrical measurement. The SEM image after the electrical measurement was shown in the Fig.S5c. The SEM micrograph reveals the fracture of the graphene beam at the anchoring ends. The reason for this phenomenon is not clear. Excessive under etching of the substrate SiO₂ beneath the anchor electrodes could be one of the possible reasons for such a failure Ref.[3]. This type of measurement failure was observed in very few devices.

Fig S. 5 – Failure of G-G NEM contact switch during the long-term measurements. (a) Low resolution switching cycle measurements on-state and off-state switching current (Ims) for each cycle. Switching current compliance limit of 5 µA was reached for over few hundred switching cycles. (b) Zoom-in view of the figure (a). (c) SEM image after the electrical measurements reveals the fracture of the graphene beam. Scale bar is 0.5 µm.
VII. A CONTROL SWITCH: GRAPHENE-METAL(CR$_2$O$_3$/AU) NEM CONTACT SWITCHES

Fig. S6 illustrates the schematic of the metal-graphene NEM contact switching devices. In this metal-graphene NEM switch the actuation electrode was fabricated without the contact graphene layer. The metal electrode (Cr/Au) was deposited by using electron beam (EB) evaporation (Fig. S6b). The total thickness of the metal electrodes was 5/85 nm (Cr/Au). A chromium metal layer of 5 nm was exposed directly above the suspended graphene ribbon and the gold was on top of the Cr metal. This Cr/Au metal stack is used as the electrode for this metal-GNEM switch. The sacrificial SiO$_2$ was released using BHF. This leads to the exposure of the chromium metal layer to atmospheric conditions and it subsequently leads to the natural oxidation of Cr to Cr$_2$O$_3$. The existence of this thin naturally oxidized chromium oxide (Cr$_2$O$_3$) layer acts as the direct contact layer for the suspended graphene ribbon. Approximately 1-2 nm thick natural Cr$_2$O$_3$ can be assumed on the surface of the metal electrode. Suspended graphene was first pulled-in onto the natural Cr$_2$O$_3$. Owing to the amorphous and uncontrolled nature of the metal electrode surface, the GNEM switch failed electrically within few switching cycles of operation.

Fig. S 6 – Schematic illustration of the Metal-Graphene NEM switch. (a) Metal-graphene NEM switch the switch was fabricated without the contact graphene layer. (b) Zoom-in view of the metal actuation electrode.

Fig. S 7 – The switching characteristics of graphene-Au/Cr contact NEM switches.
VIII. REPRODUCIBILITY OF THE G-G NEM CONTACT SWITCHES

The electrical characterisation results of the G-G NEM switches with high endurance are furnished in the Table-I. All the measured switches are maintains on/off ratio of $\sim 10^7$ orders of magnitude.

**TABLE I – Electrical characteristics obtained for various devices.**

| Switch id. | Length ($\mu$m) | Width ($\mu$m) | Airgap (nm) | Pull-in (V) | Pull-out (V) | On/Off ratio | Hysteresis (V) | Endurance (million) |
|------------|-----------------|----------------|-------------|-------------|-------------|--------------|----------------|---------------------|
| Sd1        | 1               | 0.5            | 30          | 0.45        | 0.4         | $10^8$       | 0.1            | 1                   |
| Sd2        | 1.5             | 0.5            | 30          | 1.1         | 0.9         | $10^9$       | 0.2            | 0.5                 |
| Sd3        | 1               | 0.5            | 30          | 2.0         | 1.4         | $10^8$       | 0.6            | 1                   |
| Sd4        | 1.5             | 0.5            | 60          | 1.9         | 1.4         | $10^8$       | 0.5            | 1.5                 |
| Sd5        | 1               | 0.5            | 60          | 1.9         | 1.4         | $10^8$       | 0.4            | 2                   |
| Sd6        | 2               | 0.5            | 60          | 0.45        | 0.4         | $10^8$       | 0.1            | 1                   |
| Sd7        | 1               | 0.5            | 90          | 1.1         | 0.9         | $10^9$       | 0.2            | 3                   |
| Sd8        | 1.5             | 0.5            | 90          | 2.0         | 1.4         | $10^8$       | 0.6            | 1                   |
| Sd9        | 2               | 0.5            | 90          | 1.9         | 1.4         | $10^8$       | 0.5            | 2                   |
IX. PRE-ELECTRICAL FAILURE ANALYSIS OF G-G NEM CONTACT SWITCHES

There are five different failure modes observed in graphene - graphene NEM contact switches. Out of five failure modes, two modes are exclusively raised from the fabrication process. These modes were existed even before the electrical measurement. Fig.S8 illustrates the SEM image of the failed devices. There are two types of pre-electrical measurement failure, top actuation electrode fracture and the top actuation electrode overlapping with the anchor electrode shown in Fig.S8a and S8b, respectively. It is evident from the Figure. S8a that top actuation electrode is completely broken on one end and connected with the gold contact pads on another end. It is also clearly evident that the suspended graphene beam is unaffected. The reason for such a failure may due to the undeveloped polymer residues in the exposed patterns, such polymer residues leads to the improper deposition of the metal electrodes during the electron beam deposition. Another common pre-electrical measurement failure is overlapping of the top actuation electrode with anchoring electrodes. Fig.S8b illustrates the overlapping of the top actuation electrode with the anchor electrode. This is due to the misalignment of the top actuation electrode during the pattern exposure in the electron beam lithography. These failures along with the fracture of anchor electrodes only constitute less than 25% of the total failures observed in the G-G NEM contact switches.

Fig S. 8 – Pre-electrical failure modes observed in G-G NEM contact switches. (a) SEM image of failed device caused by fracture of the top actuation electrode. (b) Failure owing to the overlapping of the top actuation electrode with the anchor electrode.
X. VARIATIONS IN THE PULL-IN VOLTAGE OF G-G NEM CONTACT SWITCHES WITH IDENTICAL DEVICE DIMENSIONS

Fig. S9 shows the pull-in voltage variation in the G-G NEM contact switches with identical device dimensions. Fig. S9a to Fig. S9e corresponds to devices shown in the main manuscript of Fig. 5a to Fig. 5e, respectively. The high-resolution G-G NEM contact switching characteristics (Is-Va) are shown for each device. It is worth noting that, the switching characteristic curves shown in Fig. S9a to Fig. S9e, are to demonstrate the pull-in voltage variation in the devices, so only the first few switching cycles were given. All devices were fabricated with identical device dimensions. The geometrical dimensions along with the measured electrical characteristics of the G-G NEM contact switches are furnished in Table-II.

TABLE II – Variations in the pull-in voltage of G-G NEM contact switches with identical device dimensions.

| Switch id. | Length (µm) | Width (µm) | Airgap (nm) | Pull-in (V) | Pull-out (V) | On/Off ratio | Hysteresis (V) | Failure Type |
|------------|-------------|------------|-------------|-------------|-------------|--------------|----------------|--------------|
| SVd1       | 1           | 0.5        | 60          | 0.7         | 0.6         | $10^8$       | 0.1            | Stiction     |
| SVd2       | 1           | 0.5        | 60          | 1.3         | 1.2         | $10^9$       | 0.1            | Stiction     |
| SVd3       | 1           | 0.5        | 60          | 2.0         | 1.8         | $10^8$       | 0.2            | Stiction     |
| SVd4       | 1           | 0.5        | 60          | 2.3         | 1.9         | $10^8$       | 0.4            | Stiction     |
| SVd5       | 1           | 0.5        | 60          | 2.6         | 2.3         | $10^8$       | 0.3            | Stiction     |
| SVd6       | 1           | 0.5        | 60          | 3.3         | 2.9         | $10^8$       | 0.4            | Stiction     |

Fig. S. 9 – Misalignment induced pull-in voltage variation in G-G NEM contact switches. (a-f) The observed pull-in voltage variation in G-G NEM contact switches with identical device dimensions, as given in Table-II. This Is-Va high resolution curves corresponds to Fig. 5f of the main manuscript.
XI. FEM ANALYSIS OF THE G-G NEM CONTACT SWITCHES

In order to understand the mechanical failure modes owing to the asymmetric electric field generated by the misalignment of top actuation electrode, a 3D finite element simulation of this G-G NEM switch was conducted by replicating the experimental device structure. The detailed FEM model of the geometry is shown in figure 6a. The FEM model was built in CAD-based tool COMSOL (V5.6, COMSOL Inc., Burlington, MA, USA). To conduct the simulation for the very thin structures effectively, the high power computational machines were used. All the simulation was done in HP Z820 with 128 GB of memory.

Fig S. 10 – FEM simulation of the G-G NEM contact switches. (a) Device structure of the G-G NEM contact switch without meshing. Each material layer is color coded with unique colors, grey, magenta, blue and yellow respectively for Si, SiO$_2$, graphene and gold. (b) Top view (YX-plane) of C-C structure. (c) Top view (YX-plane) of C-E structure. (d) 3D profile of the double-clamped graphene beam displacement for C-C structure. (e) 3D profile of the double-clamped graphene beam displacement for C-E structure. (f) The potential distribution (3D) of the switch in ZX-plane for C-C structure; Arrows illustrate the electric field direction. (g) The potential distribution (3D) of the switch in ZX-plane for C-E structure; Arrows illustrate the electric field direction.
The Fig.S10a illustrates the 3D geometry of G-G NEM contact switch in COMSOL. The top view of the the G-G NEM contact switches with centre to centre (C-C) aligned structure is shown in Fig.S10b and Fig.S10c illustrates the centre to edge (C-E) misaligned structure. The double-clamped graphene beam displacement is shown in Fig.S10d and Fig.S10f for C-C and C-E structures, respectively. The Fig.S10f and Fig.S10g respectively illustrates the electric field distribution for C-C aligned and C-E misaligned structures. The 3D image of the device is set in the ZX-plane for better visualization of the electric field distribution in both the cases. The 2D cut plane is positioned at identical special coordinates in C-C and C-E structures in order to understand the effect of misalignment induced pull-in voltage variations. It is well evident from the Fig.S10f and Fig.S10g that the electric field strength is significantly changes across the midline of the suspended graphene beam. The reduced electric field strength at the the midline of the graphene beam causes the increase of the pull-in voltage in C-E structures. In other words, owing to the reduced electric field strength, the C-E misaligned structures needs more voltage to induce the pull-in. The arrows indicates the direction of the electric field.
The literature review of high endurance NEM contact switches is compared with the G-G NEM switches and furnished in the Table-III.

**TABLE III – Literature review of high endurance NEM contact switches.**

| Material | Type | Airgap (nm) | Pull-in (V) | Pull-out (V) | Hysteresis (V) | Switching Slope (mV/dec) | Switching cycles | Reference |
|----------|------|-------------|-------------|-------------|----------------|-------------------------|-----------------|-----------|
| TiW      | 2T   | <10         | 0.4         | –           | –              | <10                     | >20             | Ref.[4]   |
| CNT      | 3T   | 30          | 45          | –           | –              | –                       | >1              | Ref.[5]   |
| TiN      | 3T   | 40          | 16          | 14          | 2.0            | –                       | >10             | Ref.[6]   |
| W, Ru    | 3T   | 100         | 5.2         | 4           | 1.2            | 0.1                     | 10^6            | Ref.[7]   |
| Pt       | 5T   | –           | 7.9         | 5           | 2.9            | –                       | >10^8           | Ref.[8]   |
| a-C      | 3T   | 60          | 6.9         | 6.4         | 0.5            | –                       | 10^8            | Ref.[9]   |
| SiC      | 3T   | 100         | 15.2        | 9.5         | 5.7            | –                       | 10^5            | Ref.[10]  |
| Ru       | 6T   | 150         | 8.9         | 7.9         | 1              | –                       | 10^7            | Ref.[11]  |
| Ni b     | 3T   | 1400        | 96          | 85          | 11             | –                       | 10^6            | Ref.[12]  |
| Ni/Au c  | 3T   | 400         | 71.8        | 65.8        | 6              | –                       | 10^7            | Ref.[13]  |
| CNT d    | 2T   | 115         | 23.4        | 20          | 3.4            | –                       | 10^6            | Ref.[14]  |
| Poly Si e| 3T   | –           | 18.7        | 16.3        | 2.4            | –                       | 10^6            | Ref.[15]  |
| Mo       | 3T   | 100         | 21.3        | 19.2        | 2.1            | 2.5                     | 20000           | Ref.[16]  |
| Graphene | 2T   | 30, 60 & 90 | ~0.5        | 0.4         | 0.1            | 10^8                    | 10^6            | This Work |

a Configuration of switch, 2T- two terminal, 3T- three terminal,...
b Ni coated with Graphene (MLG)
c Ni/Au with CNT as contact
d CNT with DLC contact
e Poly Si covered with NCG
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