Graphene-Based Nano-electro-mechanical Switch with High On/Off Ratio

Masao Nagase[1*], Hiroki Hibino[2], Hiroyuki Kageshima[2], and Hiroshi Yamaguchi[2]

[1]Faculty of Engineering, The University of Tokushima, Minami-josanjima, Tokushima 770-8506, Japan

[2]NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corp., Morinosato-wakamiya, Atsugi 243-0198, Japan

Locally defined nanomembrane structures can be produced in graphene films on a SiC substrate with atomic steps. The contact conductance between graphene and a metal-coated nanoprobe in scanning probe microscopy can be drastically reduced by inducing local buckling of the membranes. Repeatable current switching with high reproducibility can be realized. The on/off ratio can be varied from about 10^5 to below 10 by changing the contact force. At a low contact force, the contact conductance changes from 10 μS ("ON" state) to 100 pS ("OFF" state). This novel device structure could represent a new path to electrical switching at the nanoscale.

The outstanding electrical1),2) and mechanical properties3),4) of graphene make it very promising for micro- and nano-electro-mechanical systems (NEMS). While several studies have attempted purely electrical switching with graphene transistors, the on/off ratios are low due to the limitations of current band-gap engineering methods.5-7) The present band-gap engineering techniques such as quantum confinement5 and vertical electrical fields6),7) are not applicable to switching devices for integrated circuits, because their on/off current ratios do not satisfy the requirement of the International Technology Roadmap for Semiconductors (ITRS).8) Thus, devices that exploit both the electrical and mechanical properties of graphene will be more promising.

The on/off current ratio of a graphene FET is typically less than 10 and can reach a value of around 100 with band-gap engineering.6-7) Moreover, it is very difficult to control the minimum conductance of graphene FETs.5) Recently, we have found that the contact resistance between a metal probe used for SPM and a graphene nanomembrane was much higher (over 10,000 times) than that between a probe and graphene normally grown on a SiC substrate.9) This suggests that the contact resistance can be controlled with a high on/off current ratio by varying the electronic state of graphene. However, the reported graphene membrane structures9) cannot be formed at required positions on the SiC substrate, making it difficult to implement a nanomembrane-based electronic device. Thus, in this study, we tried to devise a new type of graphene NEMS switch with a high on/off current ratio on atomic steps on a SiC substrate.

A graphene sample was prepared by high-temperature annealing of a 4H-SiC (0001) semi-insulative substrate (off cut angle ~ 0) in ultrahigh vacuum.10) Low-energy electron microscopy (LEEM) confirmed that the graphene samples comprised about two atomic layers on average.11-12) Contact conductance properties between the epitaxial bilayer graphene and a metal (Rh)-coated probe were measured by using a commercial SPM apparatus (E-sweep/Nanonavi SII-NT). Since the substrate was semi-insulative, the counter electrode was put on the sample surface for ohmic contact. All SPM results were taken in constant force mode in vacuum (~$3\text{x}10^{-5}$Pa) at room temperature. Typical scan speed was ~ 1 μm/s.

In the SPM results in Fig. 1, the remarkable feature is that the contact conductance drastically changes with the scan direction. For example, the contact conductance of the central terrace in Fig. 1(c) is high ("ON") during an upward scan [Fig. 1(a)] but low ("OFF") during a downward scan [Fig. 1(b)]. As shown in Fig. 1(d), the upward scan (red line) starts with the lowest terrace, which is in the "OFF" state (low contact conductance). The contact conductance suddenly increases when the probe reaches the step edge and turns into the "ON" state. The contact conductance is modified at the second step between the middle terrace and the highest terrace. Such a conductance modification in a step region has already been reported in the literature.10) In the downward scan (blue line), the contact conductance starts in the "ON" state. At the first downward step, the contact conductance turns to the "OFF" state. Note that the contact conductance of the middle terrace during the upward scan is in the "ON" state, but the same terrace in the downward scan is in the "OFF" state. The contact conductance between the graphene and scanning metal probe drastically changed when passing the step edge. This phenomenon has complete repeatability. Current switching at the step edge steadily occurs for all scan lines in the current images [Figs. 1(a) and 1(b)]. In previously reported graphene MEMS/NEMS switches,13,14) an on-off behaviour is achieved by touching and detouching the metal electrode to the graphene membrane. It is interesting that in our structure, the nanoelectrode (the metal probe) always touches the graphene. The "OFF" state conductivity, which has a finite value, can be controlled by contact force. In the conductance profiles shown in Fig. 2(a), which were obtained at almost 0 μS, the "OFF" state current cannot be detected with the built-in amplifier of our SPM apparatus. The on/off ratio is more than 1000. At a high contact force, 600 nN, the "OFF" state conductance drastically increases to 30-60 μS, as shown in Fig. 2(b). The on/off ratio at 600 nN is about 4. A tunable on/off ratio is one of the outstanding properties of our graphene switch.

To understand what happens to the middle terrace during a scan, we examine the topographic profiles, as shown in Fig. 2. Clearly, the terraces in the "OFF" state are higher than those in the "ON" state by about 0.3 nm. The "OFF" state appears to be caused by locally suspended graphene that forms as a result of the buckling of graphene on the terrace region. The contact conductivity of suspended graphene is very low, as reported in the literature.9) The I-V characteristics of the "OFF" state shows a non-linear behaviour which is almost the same as the reported suspended graphene.9) The compressive stress in epitaxial graphene induced by the thermal expansion coefficient difference with the SiC substrate15,16) should induce buckling. The buckling height decreases with contact force to about 0.1 nm in Fig. 2(b). The distance between graphene and the substrate strongly affects the electrical properties of graphene. As illustrated in Fig. 3, upward buckling occurs when the scanning probe goes down the steps and the contact conductivity becomes low. Upward scanning cannot induce buckling and so the conductivity stays high. These simple rules can explain the switching of graphene conductivity. Thus, the mechanical bistability of graphene on SiC could be the cause of the large contact conductance modification. At this point, the details of bi-stability mechanism of graphene nano-membrane is unclear. One possible cause of bi-stability will be a lateral force (friction force) which increase at a step edge.

In addition, buckling of graphene could be induced by other methods without scanning. For example, when a metal-coated probe approaches a sample surface in an SPM instrument, attractive (van der Waals) forces between the probe and sample can produce an upward bulge.17,18) As a result, the contact conductance just after touchdown is very low, as shown in the measurements in Fig. 4(a). In the indentation mode, the measured contact conductance at a low contact force is below 10^{-10} S. This conductance value is about five orders of magnitude smaller than the contact conductance estimated from the scanning conductance images (solid squares), and the value is consistent with that in the "OFF" state previously described. The contact conductance in the scanning mode varies with the 2/3 power of the force.9) The force dependence in the scanning mode is explained by the elastic deformation of the sample and probe. In this regime, the contact conductance is proportional to the contact area. The estimated contact resistance for the normal state of graphene on SiC is about 3 nΩ cm^2 which is lower than that of the ITRS requirement (< 10 nΩ cm^2).8) However, in the indentation mode [solid circles in Fig. 4(a)], the contact conductance strongly depends on the contact force. In this case, the contact conductance should be determined by complex factors such as the graphene electronic state, distance between graphene and the substrate, and buckling diameter. Additional detailed experiments will be required to clarify the mechanisms behind buckling and its properties.

With this structure, the basic components for a graphene-based few-atomic–layer-thick NEMS switch are a step structure and a metal nanoelectrode. We measured the characteristics of such a device (Fig. 5) by carefully maintaining the contact force at almost zero by tuning of cantilever deflection. Mechanical contact was maintained by adhesion forces between graphene and the metal probe. The lateral traveling length required for current switching was a few tens of nanometers, as shown in Fig. 5(a). The estimated contact diameter between the probe and graphene was below 10 nm. The probe was repeatedly scanned along the same 100-nm-long line. The contact current profile was measured at 1 mV using a sub-femtoamp SourceMeter (Keithley 6430) in the time domain, as displayed in Fig. 5(b). The on/off ratio is stable and reaches values greater than 10^5, which satisfies the ITRS requirement of the on-off ratio for emerging research devices.[8] These results suggest that NEMS switches with a high on/off ratio can be realized by using simple structures comprising graphene on SiC and nanosized metal electrodes.

In summary, the contact conductance between graphene and a metal-coated probe drastically changes from 10 μS to 100 pS because of the mechanical bistability of the epitaxial graphene under compressive strain. The buckled state ("OFF" state) is induced by downward scanning across steps on the SiC substrate or by bringing the probe near the surface. The normal state ("ON" state) appears when the scanning probe travels up the steps. These two states are repeatedly switched by scanning the probe. These phenomena could open the path to practical graphene NEMS switches.

Acknowledgments

This work was partly supported by Grants-in-Aid for Scientific Research (Nos. 22310086, 21246006, and 20246064) from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

References

1) K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, and A. A. Firsov: Science **306** (2004) 666.

2) K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, M. I. Katsnelson, I. V. Grigorieva, S. V. Dubonos, and A. A. Firsov: Nature **438** (2005) 197.

3) J. S. Bunch, A. M. van der Zande, S. S. Verbridge, I. W. Frank, D. M. Tanenbaum, J. M. Parpia, H. G. Craighead, and P. L. McEuen: Science **315** (2007) 490.

4) C. Lee, X. D. Wei, J. W. Kysar, and J. Hone: Science **321** (2008) 385.

5) M. Y. Han, B. Ozyilmaz, Y. Zhang, and P. Kim: Phys. Rev. Lett. **98** (2007) 206805.

6) E. V. Castro, K. S. Novoselov, S. V. Morozov, N. M. R. Peres, J. M. B. L. dos Santos, J. Nilsson, F. Guinea, A. K. Geim, and A. H. C. Neto: Phys. Rev. Lett. **99** (2007) 216802.

7) J. B. Oostinga, H. B. Heersche, X. Liu, A. F. Morpurgo, and L. M. K. Vander-sypen: Nat. Mater. **7** (2008) 151.

8) International Technology Roadmap for Semiconductors. http://www.itrs.net

9) M. Nagase, H. Hibino, H. Kageshima, and H. Yamaguchi: Appl. Phys. Express **3** (2010) 045101.

10) M. Nagase, H. Hibino, H. Kageshima, and H. Yamaguchi: Nanotechnology **20** (2009) 445704.

11) H. Hibino, H. Kageshima, F. Maeda, M. Nagase, Y. Kobayashi, and H. Yamaguchi: Phys. Rev. B **77** (2008) 075413.

12) H. Hibino, H. Kageshima, and M. Nagase: J. Phys. D: Appl. Phys. **43** (2010) 374005.

13) K. M. Milaninia, M. A. Baldo, A. Reina, and J. Kong: Appl. Phys. Lett. **95** (2009) 183105.

14) S. M. Kim, E. B. Song, S. Lee, S. Seo, D. H. Seo, Y. Hwang, R. Candler, and K. L. Wang: Appl. Phys. Lett. **99** (2011) 023103.

15) Z. H. Ni, W. Chen, X. F. Fan, J. L. Kuo, T. Yu, A. T. S. Wee, and Z. X. Shen: Phys. Rev. B **77** (2008) 115416.

16) J. Röhrl, H. Hundhausen, K. V. Emtsev, Th. Seyller, R. Graupner, and L. Ley: Appl. Phys. Lett. **92** (2008) 201918.

17) J. M. Soler, A. M. Baro, N. Garcia, and H. Rohrer: Phys. Rev. Lett. **57** (1986) 444.

18) N. N. Klimov, S. Jung, S. Zhu, T. Li, C. A. Wright, S. D. Solares, D. B. Newell, N. B. Zhitenev, and J. A. Stroscio: Science **336** (2012) 1557.

Figure captions

Figure 1. SPM results for graphene on SiC. a,b, SPM current images measured at contact force of 180 nN. The sample bias is 0.5 mV. (a) Current image along upward (left to right) scan direction. (b) Current image in downward (right to left) scan direction. (c) Topographic image of measured area. (d) Conductance profiles for the middle step [dashed line in (c)]. In Fig. 1(a), the lowest (left-hand) terraces are dark (“OFF”). In Fig. 1(b), only the highest (right-hand) terrace is bright (“ON”). Current switching occurs just at a step edge. The contact conductance of bright areas is about 50 μS and that of dark areas is about 1 μS; the conductance ratio of bright to dark areas is about 40.

Figure 2. Conductance and topographic profiles for three terraces of graphene on SiC. Contact force set at ~0 nN for (a), and 600 nN for (b). In the “OFF” state in Fig. 2(a), the current is below the detection limit (10 pA) of the built-in amplifier of our SPM apparatus. The buckling heights measured from the differences between the second terrace heights in both scan directions are 0.5 nm for ~0 nN and 0.1 nm for 600 nN. The contact force is controlled by the cantilever (3 N/m) deflection. At zero contact force, the contact between the sample and probe is maintained by adhesion forces.

Figure 3. Schematic of proposed few-atomic-layer graphene switch. Local buckling of graphene is induced by downward scanning at the step edge. The buckled graphene (partially suspended nanomembrane structure) turns into the low-contact-conductance (“OFF”) state. The buckling disappears at the step edge in upward scanning.

Figure 4. Dependence of contact conductance on contact force. Solid squares (scanning mode) indicate conductance measured from several current images. These plots represent the “ON” state.

In the scanning mode, the conductance is proportional to the contact area defined by the elastic deformation of the sample and probe, as illustrated in the right-top inset figure. The contact conductance is proportional to the 2/3 power of the contact force, as indicated by the solid line. Solid circles represent the contact conductance in the indentation mode. The approaching probe induces buckling of the graphene membrane because of the van der Waals forces. The contact conductance in the buckling ("OFF") state increases with the contact force. In the indentation mode, the probe is not scanning.

Figure 5. Current switching by few-atomic-layer graphene switch. (a) Plot of distance against contact conductance. The traveling length is 100 nm. The "ON" to "OFF" state transition distance is about 20 nm. (b) Repeatability of switching behaviour. The arrow indicates the position of Fig. 5(a).

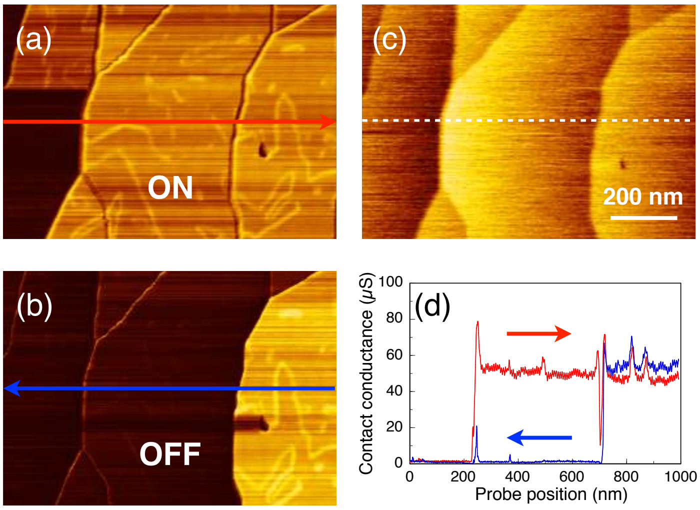
(a)
ON
(c)
200 nm
(b)
OFF
(d)
Contact conductance (μS)
0
20
40
60
80
100
0
200
400
600
800
1000
Probe position (nm)

Fig. 1

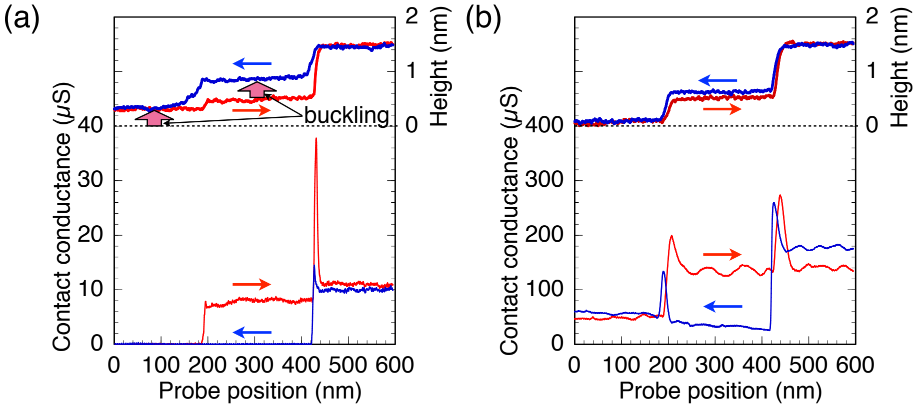
(a)
buckling
Contact conductance (μS)
0
10
20
30
40
Height (nm)
0
1
2
0
100
200
300
400
500
600
Probe position (nm)
(b)
Contact conductance (μS)
0
100
200
300
400
Height (nm)
0
1
2
0
100
200
300
400
500
600
Probe position (nm)

Fig. 2

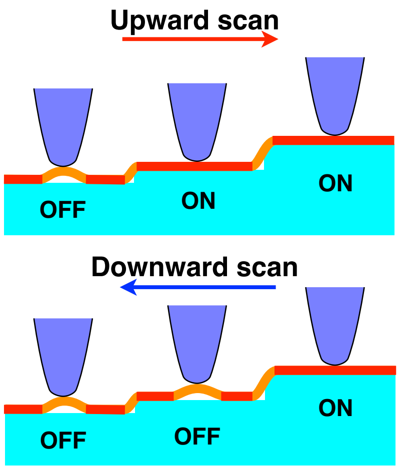
Upward scan
OFF
ON
ON
Downward scan
OFF
OFF
ON

Fig. 3

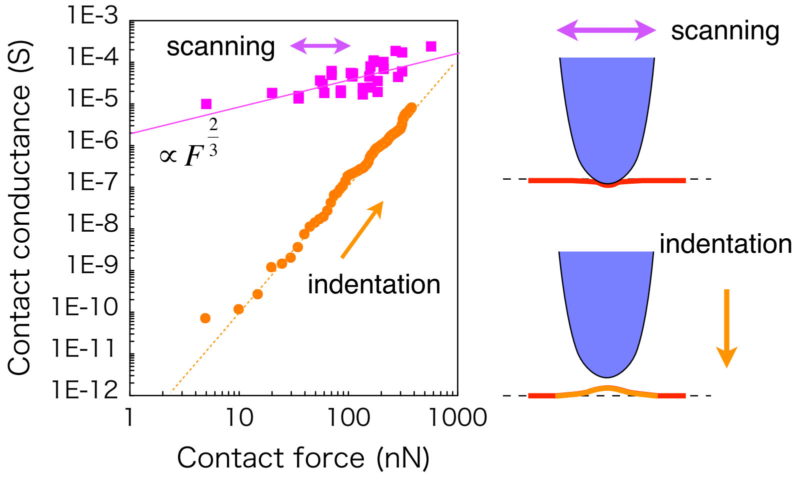
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
1E-11
1E-12
Contact conductance (S)
1
10
100
1000
Contact force (nN)
scanning
$\propto F^{\frac{2}{3}}$
indentation
scanning
indentation

Fig. 4

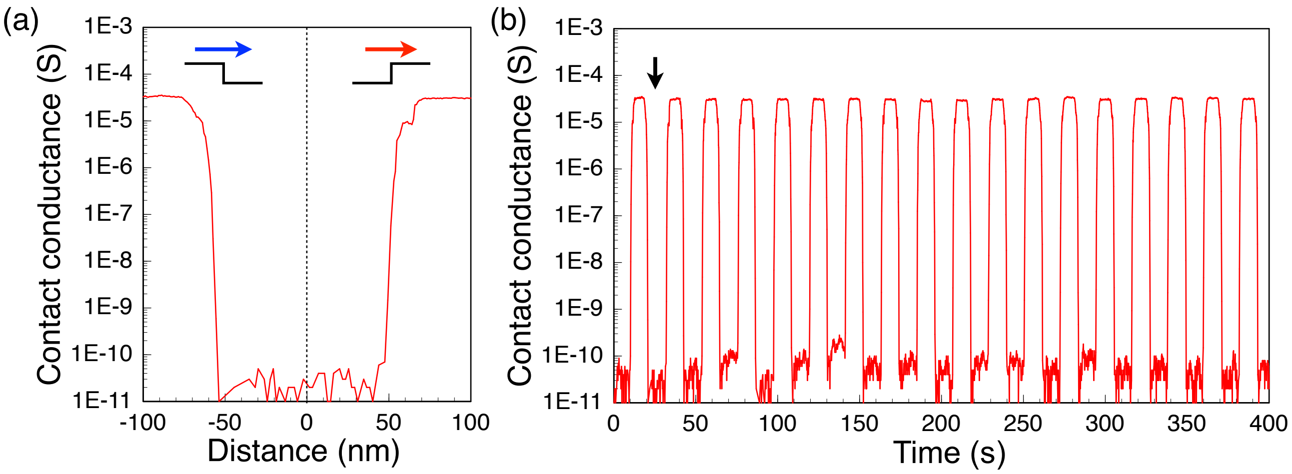
(a)
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
1E-11
Contact conductance (S)
-100
-50
0
50
100
Distance (nm)
(b)
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
1E-11
Contact conductance (S)
0
50
100
150
200
250
300
350
400
Time (s)

Fig. 5