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Author(s)	王，文楨
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Description	Supervisor:水田　博，マテリアルサイエンス研究科，博士

Japan Advanced Institute of Science and Technology

ABSTRACT

Energy and Environment Research Division

School of Material Science

Mizuta Laboratory

Doctor of Philosophy

Graphene-based Nanoelectromechanical (NEM) Switching Devices

BY WENZHEN WANG

Nanoelectromechanical (NEM) switch has become one of the promising candidates to overcome the limitations of conventional CMOS technology, which can offer extremely low leakage current, abrupt switching (SS < 3 mV/dec) and high ON/OFF ratio. By taking the advantages of graphene, which are atomic thin and high Young's modulus, we can further reduce the pull-in voltage and scale down the size of graphene NEM switches. An autonomous GNEMS sensor system was proposed by Prof. Hiroshi Mizuta in 2013. Graphene NEM switch is planned to be utilized as a power gating device to shut down the power supply at the sleep-mode of sensor, thus saving the total energy dissipation. Currently, the critical issue, which hinders the development of graphene NEM contact switches, is the device reliability. The irreversible stiction at the contact often occurred, as the most common failure mode of graphene NEM switches. Au-C chemical bonding was recognized, originating from the permanent stiction, which should be excluded from the switch design.

The aim of this study is to achieve stable switching operations of graphene NEM switches. To avoid the direct contact between graphene to metal, naturally grown oxide was selected as the contact material with graphene. The novel graphene contact devices, which combined transmission line method pattern (TLM) pattern with graphene NEM top-gated switches, were fabricated, intended to comprehensively investigate the graphene contact issues. In addition, periodic concave patterns were introduced into the contact interface to reduce the stiction. Static contact between graphene and Cr were studied from the TLM patterns, which indicated slightly negative values of static contact resistance owing to the doping from the metal and the substrate. All the dynamic GNEM contact switches showed clear pull-in operations, however, none of those switches demonstrated the pull-out operations owing to a strong adhesive force. By analysing the measured contact resistance and contact pressure, plastic deformation of the Cr_2O_3 layer was discussed at the graphene-Cr_2O_3 contact interface, which resulted in the increase of vdW force, thus the irreversible stiction.

To reduce the stiction force, the periodic concave patterns at the bottom surface of the top gate were changed to the tip structures to further reduce the contact area. Besides, comparing with the geometry of GNEM switches studied in dynamic contact, shorter graphene beam length and larger air gap distance from suspended graphene to top gate were applied to the new design, aiming to increase the mechanical restoring force against the adhesive force. Additionally, the thickness of Cr_2O_3 was increased to around 2 nm to avoid the Joule heating due to the tunnelling current. After characterizing the redesigned graphene NEM switches, the hysteresis with clear pull-in and pull-out operations was observed first, but the pull-out operation was not observed in the 2^{nd} cycle and after. We have attributed this phenomenon to the stored charge in the thicker Cr_2O_3 layer, which induced extra stiction force, resulting in the non-volatile operation. Moreover, an unexpected bi-stable NEM switch was realized experimentally by reversing the bias voltage on top electrodes. This was mainly due to the charge injection with opposite polarity to the Cr_2O_3, canceling the build-up charge in dielectric and further reducing the stiction force. A novel graphene NEM non-volatile logic device was interpreted from the bi-stable switching behaviour, offering the possibility for the instant-off and instant-on applications, further to be applied as a sleep transistor to the system to cut-off the standby energy consumption.

Keywords: NEMS, Graphene, Switch, Contact, Charge storage