Field Effect Transistors with Atomically Precise Graphene Nanoribbons

Juan Pablo Llinas[1], Andrew Fairbrother[2], Gabriela Barin[2], Pascal Ruffieux[2], Kyunghoon Lee[1], Byung Yong Choi[1,3], Rohit Braganza[1], Zahra Pedramrazi[4], Chen Chen[4], Nicholas Kau[4], Akimitsu Narita[7], Tim Dumslaff[6], Xinliang Feng[6], Klaus Müllen[7], Felix Fischer[5], Michael Crommie[4], Roman Fasel[2], Jeffrey Bokor[1]
[1]Dept. of Electrical Engineering and Computer Sciences, UC Berkeley, Berkeley, CA, USA
[2]Empa, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, CH
[3]Flash PA Team, Semiconductor Memory Business, Samsung Electronics Co. Ltd., Korea
[4]Dept. of Physics, UC Berkeley, Berkeley, CA, USA
[5]Dept. of Chemistry, UC Berkeley, Berkeley, CA, USA
[6]Center for Advancing Electronics Dresden, TU Dresden, Dresden, DE
[7]Max Planck Institute for Polymer Research, Mainz, DE
jpllinas@berkeley.edu

Graphene changes from semi-metallic to semiconducting when charge carriers are confined to quasi 1-dimensional graphene nanoribbons (GNRs). The electronic properties of GNRs can be engineered for high performance and low-power semiconducting device applications by varying their width and edge structure. However, traditional methods to pattern GNRs, such as unzipping carbon nanotubes or lithographic techniques, yield GNRs with rough edges which degrade electronic transport. Recently, bottom-up chemical synthesis of graphene nanoribbons with atomically smooth and well-defined edges has been demonstrated [1]. By varying the structure of the monomer used in the polymerization step of the synthesis, the edge structure and width of the GNRs can be controlled. Field-effect transistors (FETs) fabricated with 7 atom wide GNRs (7AGNRs) have shown low driving current of 1 nA for 1 V drain bias due to the large Schottky barrier at the contacts caused by the large band gap of 7AGNRs (~3 eV) [3]. Very-large scale circuit integration requires driving currents that are at least three orders of magnitude larger than this. By measuring the electrical characteristics of FETs with 9 and 13 atom wide GNRs, we demonstrate a two order magnitude improvement in current over the 7AGNRFET.

We fabricated field effect transistors using 9-atom and 13-atom wide armchair GNRs (9AGNRs and 13AGNRs, respectively). As previously demonstrated, the synthesis for these GNRs takes place on an Au(111)/mica substrate and the width is defined by the monomer used during polymerization [1],[2]. The quality of the GNRs are verified by scanning tunneling microscope (STM) imaging, as shown in Fig. 1. Fabrication of GNRFETs requires the transfer of GNRs from the Au surface to an insulating surface. We transferred the GNRs by cleaving the mica in 38% HCl and picking up the floating gold film with a 50 nm SiO_2 / p++ Si substrate. Subsequent gold etching yields isolated GNRs on the SiO_2 surface. Since the GNRs are only tens of nanometers long, we employed electron beam lithography and lift-off processing to pattern 10 nm thick, 100 nm wide Pd electrodes with ~15 nm channel length. The final device structure is illustrated in Fig 1. Using the same fabrication methods, we made two different chips: one with 9AGNRs and 13AGNRs. Finally, we characterized the electrical transport properties of individual devices.

For the 9AGNR and 13AGNR chips, 28 devices and 29 devices were fabricated, respectively. All the devices showed semiconducting behavior with on-off ratios in the range of 10^2 to 10^5 and an on-state performance distribution shown in Fig. 2. Both the 9AGNRFETs and the 13AGNRFETs showed similar performance and behavior due to their similar band gap. All the devices are p-type with a positive threshold gate voltage in ambient conditions. However, when the devices are measured in vacuum at room temperature, the threshold voltage shifts towards 0 V as shown in Fig. 2. This effect has been observed in CNTFETs and is attributed to the charge trapping of water molecules in the vicinity of the CNT causing hysteretic effects on the gate control [4]. Since we expect GNRFETs with transparent contacts to conduct more than 1 μA at this bias (as opposed to 100 nA in our devices), we measured the devices in vacuum at varying temperatures to study the transport mechanism at the contacts.

We measured the devices in vacuum at 77 K, 140 K, 210 K, and 300 K. As shown in Fig. 3 there is no noticeable change in conduction at these different temperatures for either 13AGNRFETs or 9AGNRFETs. This weak temperature dependence in conduction indicates the occurrence of tunneling through the barriers as opposed to thermionic emission over the barriers at the contacts. Tunneling contacts with weak temperature dependence have been observed for CNTFETs and verified via simulations [5].

We demonstrated that both of these types of devices showed significant performance improvement over the previously reported 7AGNRFET and showed no temperature dependence in their behavior. Further work is needed to improve the contact resistance of GNRFETs and to reduce device-to-device variability.

[1] Cai, J. et al. Nature **466**, 470–473 (2010).
[2] Chen, Y.-C. et al. ACS Nano **7**, 6123–6128 (2013).
[3] Bennett, P. B. et al. Applied Physics Letters **103**, 253114 (2013).
[4] Kim, W. et al. Nano Lett. **3**, 193–198 (2003).
[5] Appenzeller, J., Radosavljević, M., Knoch, J. & Avouris, P. Phys. Rev. Lett. **92**, 048301 (2004).

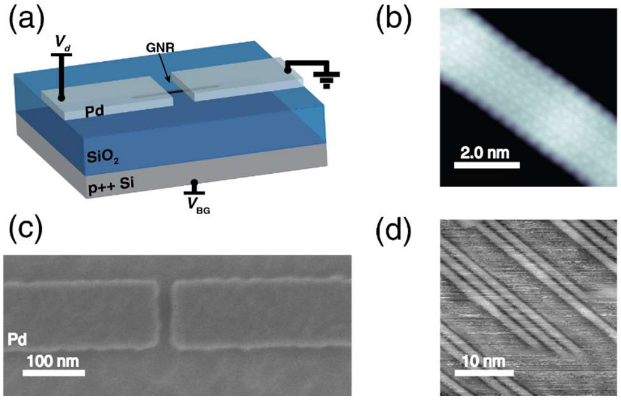

Figure 1. (a) Schematic of the fabricated GNRFETs. (b), (d) STM image of synthesized 13AGNR and 9AGNR on Au (111). (c) SEM image of the Pd source-drain electrodes.

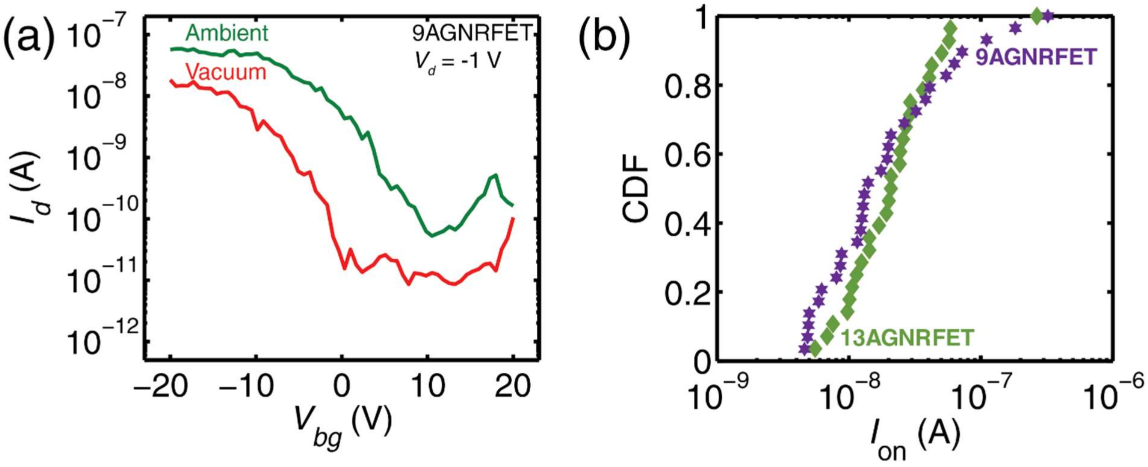

Figure 2. (a) I-V characteristics of an 9AGNRFET in vacuum and in ambient conditions. (b) Cumulative distribution function of on-current in our 9AGNRFETs and 13AGNRFETs

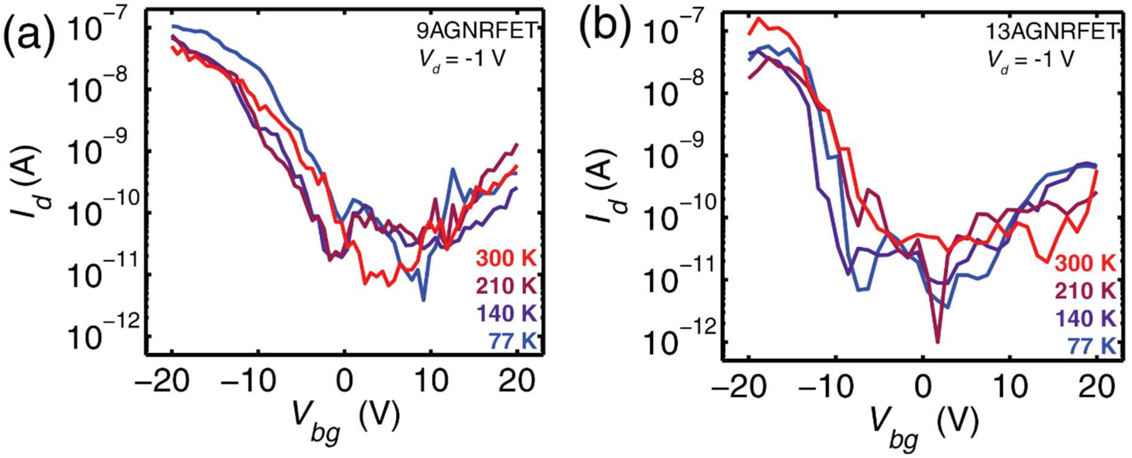

Figure 3. Temperature dependence of I-V characteristics of 9AGNRFET (a) and 13AGNRFET (b).