# Analog and digital flexible nanoelectronics fabricated from advanced 2D nanomaterials

Li Tao,[1,*] Hsiao-Yu Chang,[1] Jongho Lee[1], Huifeng Li,[2] Richard D. Piner,[2] Rodney S. Ruoff,[2] and Deji Akinwande[1,*]
[1]*Microelectronics Research Center, The University of Texas at Austin, TX 78758*
[2]*Dept. of Mechanical Engineering, The University of Texas at Austin, TX 78712*
[*]*Email: deji@ece.utexas.edu; tao@utexas.edu;*

Plastic or flexible electronics possess unique potential to enable unconventional applications such as bendable or wearable devices. One of the current demand in this art is high-frequency or high-speed transport,[1,2] which requires integrating high quality channel material compatible with flexible substrates. Although 2D materials, such as graphene or $MoS_2$, have been demonstrated for this aim, the resulting devices still suffer from inferior performance than counterparts realized on hard substrates owing to associated material, thermal and process issues. Herein, we report our recent efforts on integrating 2D material into plastic nanoelectronics that enable both high performance RF (Figure 1a) and digital (Figure 1b) functional modules.

As an example for RF applications, flexible graphene field-effect transistor (Figure 1a) was fabricated using embedded-gate fabrication process similar to our previous report,[3] and sets a highest mobility reported so far on polyimide plastic substrates. This comes from a recent progress in newly developed method for graphene synthesis and careful transfer. Electrostatic measurements yield mobility up to 6,672 $cm^2/Vs$ (Figure 2), comparable to reports on exfoliated graphene,[4] indicating that high-frequency GHz flexible systems, amplifiers, and frequency doublers on plastic substrate is a realistic prospect in the near future.[3] In addition, our study implies that extra-high quality graphene could deliver the same performance with conventional dielectrics, e.g. $SiO_2$ or $Al_2O_3$, without employing 2D gate dielectrics like *h*BN that is currently a challenge to controllable synthesize with high quality.

Compared to zero bandgap graphene, $MoS_2$ is another complementary type of 2D material that could fulfill the needs of flexible digital devices. As shown in Figure 1b, field effect transistor with 5-15 nm thick $MoS_2$ were fabricated on $H_fO_2$ dielectrics. To build $MoS_2$ devices on a polyimide substrate is not straight-forward from existing reports on hard substrates, due to several key issues. For instance, surface cleaning and material transfer have been investigated for reliable device fabrication. A recent result with field effect mobility of 20 $cm^2/Vs$ and ON/OFF ratio of $>10^7$ (Figure 3a) had been achieved and can be further improved.[5] As seen in Figure 3b, the mobility also remains stable at different bending radii up to 1 mm. To our knowledge, this is a pioneering result of flexible $MoS_2$ devices on polyimide plastics with reliable performance.

In this work, we have demonstrated flexible nanoelectronics integrated with graphene and $MoS_2$. With recent progress in material synthesis, device configuration and fabrication, our flexible RF or digital devices exhibited comparable performance to counterparts on conventional Si or quartz substrates.

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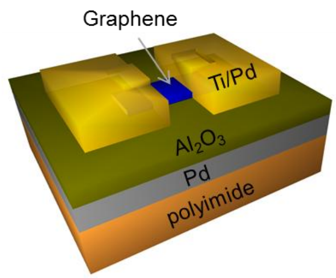


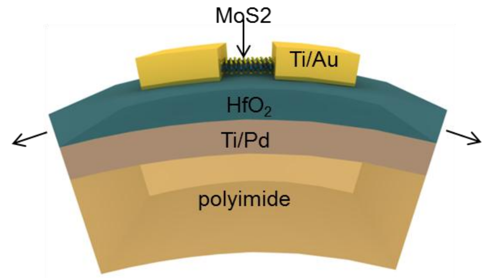


*Figure 1a: Graphene field-effect transistor on on polyimide with embedded metal gate and $Al_2O_3$ gate dielectrics.*

*Figure 1b: MoS2 field-effect transistor on polyimide with HfO2 gate dielectrics that can be subject to bending test.*

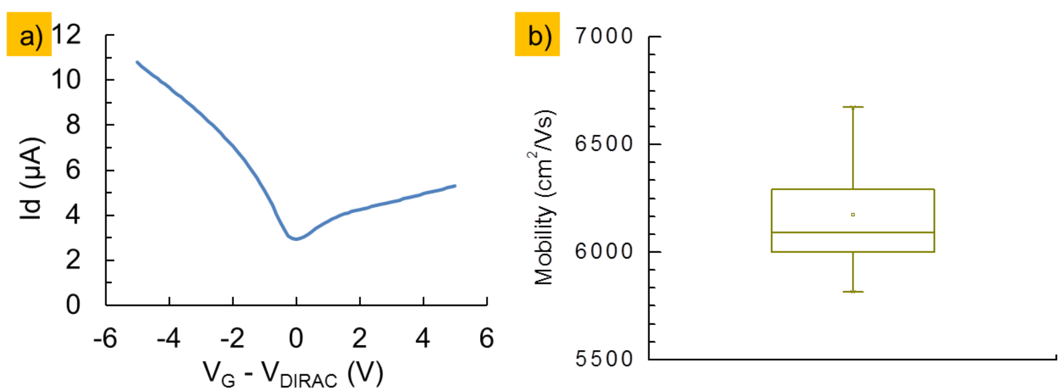


*Figure 2: Electrical characterization of flexible graphene field-effect transistors on polyimide: a) a representative Id-Vtg curve and b) box statistical analysis indicated highest mobility ~6,672 $cm^2$/Vs, the highest value achieved on flexible substrate to date.*

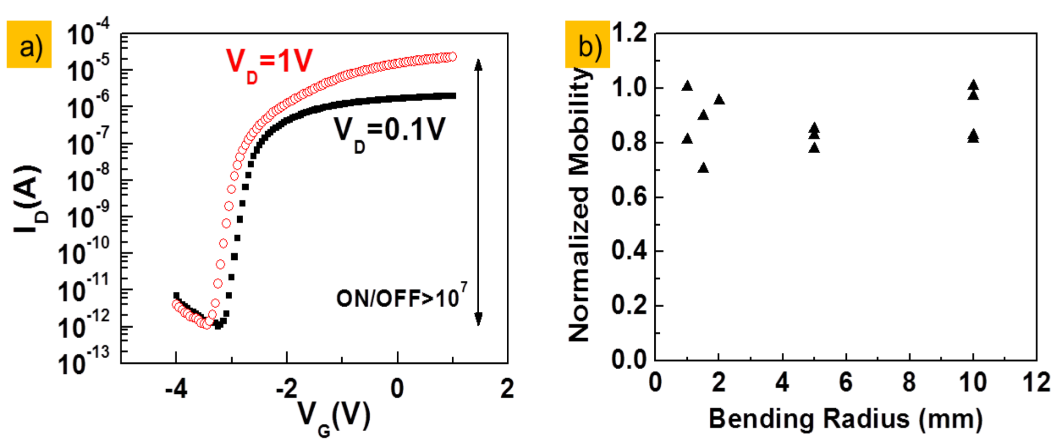


*Figure 3: The electrical characterization of $MoS_2$ devices fabricated on polyimide substrates*: a) a high ON/OFF ratio of 7 orders of magnitude with mobility around 20 $cm^2$/Vs was observed; b) the bending test indicates that the device performance remains stable at different bending radii.