Possible Electronic Device Applications of Graphene Nanoribbons

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Introduction

Recent progress of graphene nanoribbon (GNR) fabrication has demonstrated the possibility of obtaining nano-width GNRs, which have been considered as the potential materials for the next generation electronic devices due to their unique properties, such as purely spin polarization, and bandgap tunability by controlling either their width or the external electric/magnetic field [1-7]. For examples, the application as field-effect-transistors (FETs) grew a large interest from the nanoelectronics device research community in the search of an alternative channel material that might overcome the physical scaling limitations of the Si-based nano-scale MOSFETs and the fabrication challenges of carbon nanotube (CNT) FETs. Recent experimental studies indicate the possibility of fabricating GNR transistors, and highlight the potential of GNRs as an alternative to CNT, bypassing the chirality challenge while still retaining the excellent electronic properties such as high electron/hole mobility. Moreover, the electronic structure of GNRs can be controlled by their orientations and widths. Therefore, these promising properties provide the excellent basis for different types of 1D device applications based on GNR. In this work, the fundamentals of the GNRs will be introduced first. Then, based on their promising and unique properties, the theoretical aspects of different possible device applications using GNR, as listed below, will be discussed based on quantum transport calculations (non-equilibrium Green's function approach—NEGF).

Results and Discussion

(a) GNR Tunneling FETs (TFETs). TFETs have received increasing interest due to their great potential in achieving low standby power, a low subthreshold swing (SS), and the ability to provide a relatively higher ON-state current (ION) at room temperature compared to traditional TFETs. More specifically, recent theoretical studies of heterojunction TFETs, such as using GNR heterostructures with different width GNRs, and carbon nanotube-GNR heterojunctions, demonstrate promising performance with much larger ION compared to homogeneous case. However, it has been shown that the source and drain doping concentrations play an important role in device performance of conventional TFETs and hence, it would be interesting to investigate how they affect HJ GNR TEFTs. In this work, therefore, 1.1 nm wide GNR HJ TFET with double-gated structure (as shown in Fig. 1) is selected to investigate this issue based on the quantum transport simulations. We found that the OFF-state current (IOFF), ION and SS vary significantly with the source doping concentrations at a fixed drain doping; while the I_{OFF} is virtually drain doping concentration dependent at a fixed source doping. Hence, by choosing appropriate asymmetric source-drain doping concentrations, the device performance of HJ GNR TFETs can be further optimized. [4,5,8]

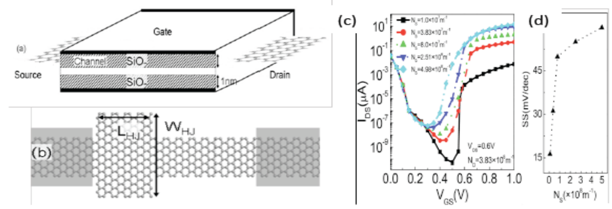

Fig. 1(a) The side (b) top views of a double-gated HJ GNR TFET. The gate insulator is silicon dioxide with a thickness of 1 nm. The gate length of the device is kept constant at 16 nm. The length and width of HJ region are L_{HJ} =2nm and W_{HJ} =2.5nm, respectively. A constant drain bias of 0.60 V is applied for all the devices simulated. (c) The I_{DS}-V_{GS} of HJ GNR TFET with the fixed N_D under different N_S = 0.1, 0.383,0.8, 2.51 and 4.98×10^8 m^{-1}. (d) The average subthreshold swing (SS) degrades with increasing N_S.

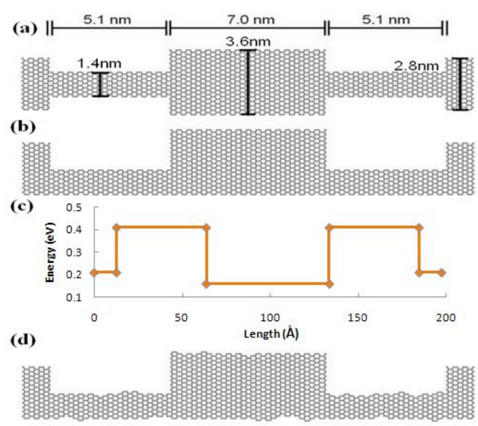

Fig. 2: An atomic representation of the (a) H- and (b) W-shape GNR RTD. The left and right barriers consist of 1.4nm wide GNR and their length is 5.1nm. The middle region is 3.6nm wide with length of 7.0nm. Due to the different ribbon width and hence different energy gap, a double barrier quantum well configuration as shown in (c) can be constructed, regardless the shape of the device. (d) A sample of the W-shape GNR RTD with 15% edge roughness.

(b) GNR resonant tunneling diodes (RTDs). RTDs are inherently high-speed devices with a special load curve that contains a region of negative differential resistance (NDR) and they have been suggested as an alternative device to the complementary metal-oxide-semiconductor (CMOS) device in high-speed information procession applications in the 2007 edition of the ITRS. Different high-speed application circuit designs have been demonstrated using RTDs in combination with other well-developed devices. A classic example is the monostable-bistable transition logic element (MOBILE) configuration which can be used for ultra high speed analog-to-digital convertor. One major challenge of RTDs is in the multilayer heterostructure which is required for the double barrier quantum well (DBQW) configuration which is responsible for the NDR characteristics of RTDs. This challenge could be mitigated using GNRs, and the DBQW can be setup by controlling the width of the GNRs as shown in Fig. 2. Furthermore, the high carrier mobility of GNR could potentially increases the drive current of RTDs and opens up other possible application. However, edge roughness remains a major concern for GNR devices. Therefore, in this work, we report our computational study on the effect of edge roughness on the device performance of GNR RTDs. [9-10]

(c) Magnetic switches: The zeroth Landau level (n=0 LL) of graphene sheet under a magnetic field is another interesting property. For other materials, LLs are created inside either the conduction band or the valence band, and these LLs shift as the applied magnetic field changes. However, for graphene sheets, as well as GNRs, one of these LLs (n=0) has been discovered at Dirac points which will remain at the same position under an varying magnetic field, without the consideration of the spin split induced by the Zeeman effects, due to the presence of massless relativistic particles. Based on this unique characteristic, we first study the magnetic field effects on electron transport in GNRs through the n=0 LL. The device physics and performance enhancement using heterostructures tunneling junctions will be further discussed. Furthermore, a large magnetoresistance effect can be obtained at room-temperature by using p-i-n armchair-GNR heterostructures as shown in Fig. 3. The key advantage is the virtual elimination of thermal currents due to the presence of band gaps in the contacts. The current at B=0T is greatly decreased while the current at B>0T is relatively large due to the band-to-band tunneling effects, resulting in a high magnetoresistance ratio, even at room-temperature. [6,11]

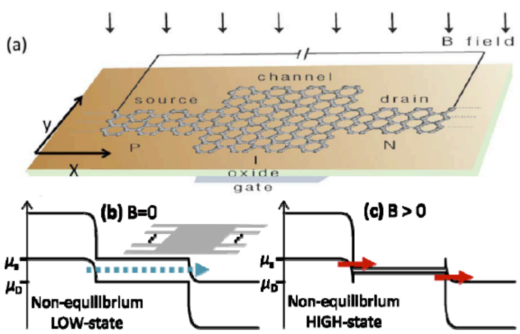

Fig. 3 (a) A schematic of a back-gate p-i-n heterostructure AGNR device, consisted of the p-type source, intrinsic channel, and n-type drain. The external magnetic field is applied to modulate the bandgap of AGNRs in order to obtain MR. (b) and (c) schematics of band profile under B=0 T and B > 0, identified as LOW-state and HIGH-state, respectively. For the former, the thermal current is eliminate by bandgap of the source and drain and the current is contributed by direct tunneling across the channel, resulting in a very low current. However, for the latter, the bandgap decreases due to the magnetic field, thus creating an overlap between the channel and the source/drain. Therefore, electrons are able to tunnel easily, and contribute a large HIGH-state current, hence resulting in high MR effects of p-i-n AGNR devices even at room temperature. The inset in (b) shows the multiple source-drain channel strips used in the simulation.

(d) Thermal Spin effects in Zigzag GNRs (ZGNRs). Magnetoresistance (MR) effect plays a key role in the digital storage applications such as hard disks. GNRs have been theoretically predicted and experimentally demonstrated to show MR effect by applying a voltage bias or temperature difference between the source and drain. For example, a remarkable thermal MR effect in a magnetized zigzag GNR (M-ZGNR) by removing the applied magnetic field has been studied and attracts a lot of attention because these MR devices can be operated powerlessly due to the absence of external electric bias but with temperature difference instead. Furthermore, thermal MR effect offers a solution to directly utilize waste heat, which provide the significant step toward "green" spintronic technology. Therefore, in this work, we study the MR effect in a ZGNR with a temperature bias as shown in Fig. 4. We find that large MR can be obtained in ZGNR. Moreover, the value of MR as a function of temperature difference can be manipulated over a wide range by selecting the magnetic configurations. Our findings indicate that ZGNRs could be one of the promising candidatures for MR application in spin caloritronics. [12]

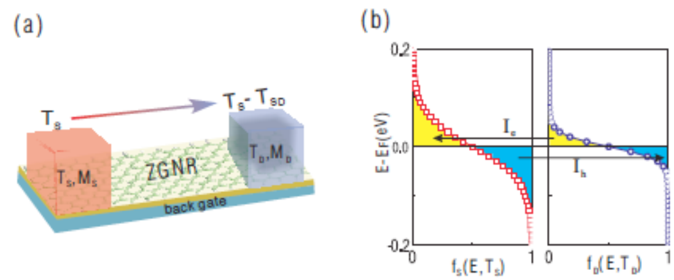

Fig. 4 (a) The schematic illustration of ZGNR-based thermal spin devices for MR application. (b) The Fermi distribution of the source (the left panel-higher temperature) and the drain (the right panel-lower temperature).

Conclusion

Based on the different unique properties of graphene-based materials (graphene nano ribbons), we have introduced their various device applications. The results show that GNRs can potentially be applied to different types switches for the future nanoelectronics devices. However, the details device designs and performance optimization need to be further investigated in this emerging field.

Acknowledgement

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