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Application of Graphene and Graphene Nanoribbons to Electronic Devices

Graphene has excellent electrical, thermal, and mechanical properties and is a promising candidate for materials of future electronic devices. Although graphene does not have a band gap, a graphene nanoribbon (GNR), a narrow strip of graphene, can have a band gap, and therefore be applied to devices such as diodes and transistors. We have been working on synthesis of nanocarbon materials and their application to electronics, including transistors and interconnects, for years. In this talk, we describe some of such applications.

One of the applications is a gas sensor. We recently developed a graphene-gate transistor, where the gate of a Si transistor is replaced with single-layer graphene (Fig.1) [1]. This graphene-gate transistor can be used as a gas sensor. In fact, when gas molecules adsorb on the graphene-gate surface, the Fermi level or work function of graphene can change, thus shifting the threshold of the Si transistor. This causes changes in the drain current if the gate voltage is kept constant. This graphene-gate sensor is very sensitive to NO_2 and NH_3. Normalized drain current of a graphene-gate sensor with time for NO_2 exposure is shown in Fig. 2. As can be seen in the figure, the sensor can detect NO_2 with concentrations less than 1 ppb.

Graphene can also be used for detecting high-frequency wave [2, 3]. We have recently proposed a diode consisting of a graphene nanoribbon heterojunction (Fig. 3) for high-frequency wave detection [4]. The heterojunction consists of a hydrogen-terminated armchair-edge GNR (H-AGNR) and fluorine-terminated armchair-edge GNR (F-AGNR). Since there is a difference in electron affinity between H-AGNR and F-AGNR, we can construct a staggered-type lateral heterojunction p-n diode. First principle calculations have shown that, due to band-to-band tunneling, the diode has a nonlinear reverse current of the order of kA/m. Furthermore, the junction capacitance is extremely small because of the small junction area. The voltage sensitivities of a backward diode as a function of frequency obtained numerically are shown in Fig. 4. The GNR-based backward diode can have a much better voltage sensitivity for high-frequency wave than a GaAsSb/InAlAs/InGaAs heterojunction diode [5].

We try to form graphene nanoribbons having various widths and edge-terminations using a bottom-up approach [6]. Figure 5 shows a scanning tunneling microscope image of H-AGNR we formed. In fact, we used a precursor shown in Fig. 6, aiming at synthesizing partially F-terminated AGNRs. The F atoms at GNR edges, however, were detached during the cyclodehydrogenation of partially edge-fluorinated polyanthrylenes to form GNRs. We have found by first principles calculations that a critical intermediate structure, obtained as a result of H atom migration to the terminal carbon of a fluorinated anthracene unit in polyanthrylene, plays a crucial role in significantly lowering the activation energy of carbon−fluorine bond dissociation.

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References

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[6] H. Hayashi, et al., ACS Nano, DOI: 10.1021/acsnano.7b02316.

Figures

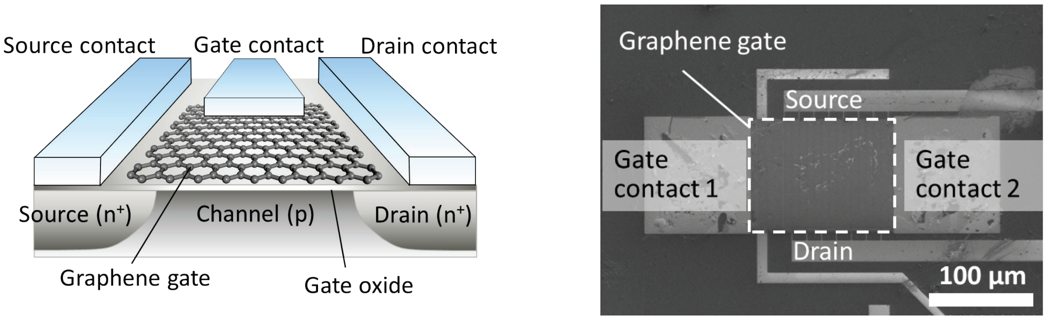


Figure 1: Schematic illustration (left) and scanning electron microscope image (right) of a graphene-gate transistor (sensor)

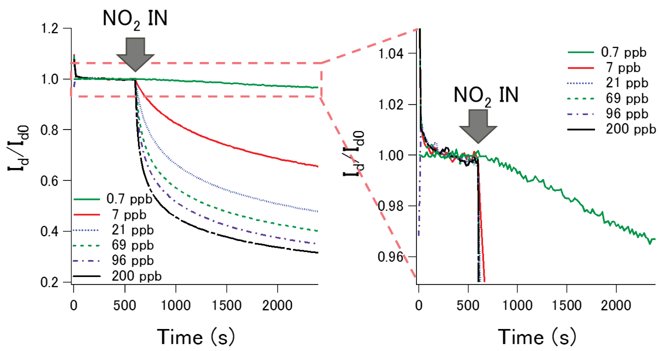


Figure 2: Dependence of the response (normalized drain current, Id/Id_0) of a graphene-gate sensor on NO_2 concentrations.

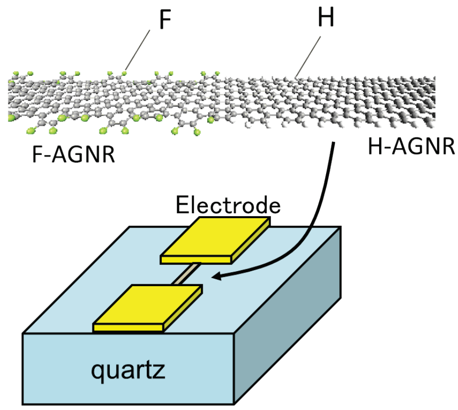
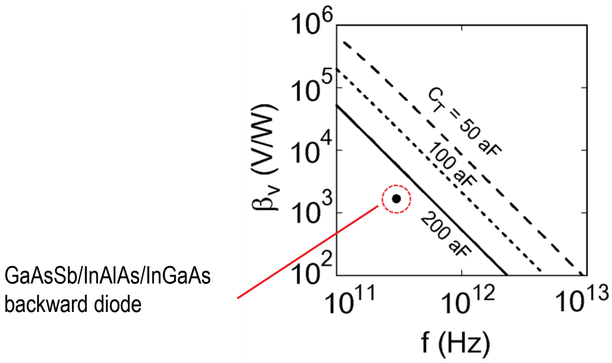


Figure 3: Illustration of a diode using a heterojunction of F-AGNR and H-AGNR.



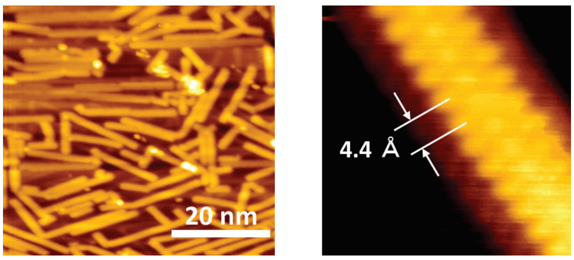


Figure 4: Calculated voltage sensitivity of a GNR diode, β_v, as a function of frequency with the total capacitance, C_T, as a parameter. The closed circle indicates β_v of a GaAsSb/InAlAs/InGaAs diode in Ref. 5.

Figure 5: Scanning tunneling microscope images of H-AGNRs

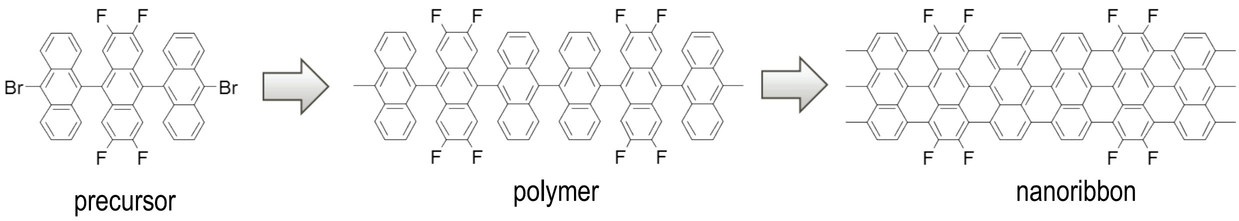


Figure 6: Scheme for synthesizing partially F-terminated AGNRs