
Application of Graphene and Graphene Nanoribbons to Electronic Devices Including Ultrasensitive Gas Sensors

Graphene, two-dimensional honeycomb carbon lattice, has excellent electrical properties, and is therefore a promising material for future electronic devices. We have been working on growth of nanocarbon materials, including graphene and carbon nanotubes, and their application to electronic devices, such as transistors, interconnects, and sensors. Furthermore, we recently work on bottom-up synthesis and application of graphene nanoribbons (GNRs). We here describe our recent progress.

We recently developed a gas sensor based on a graphene-gate transistor, where the gate of a Si transistor is replaced with monolayer graphene (Fig.1) [1]. If gas molecules adsorb on the graphene-gate surface, the Fermi level or work function of graphene can change, thus shifting the threshold of the transistor. This causes changes in the drain current if the gate voltage is kept constant. This graphene-gate sensor was found to be very sensitive to NO₂ and NH₃. As can be seen in the Fig. 2, the sensor can detect NO₂ with concentrations less than 1 ppb.

Graphene can also be utilized for high-frequency wave detection [2, 3]. We actually proposed a diode consisting of a GNR heterojunction (Fig. 3) for such a purpose [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 them, we can construct a staggered-type lateral-heterojunction p-n diode. First principles simulations show that, due to band-to-band tunneling, the diode has a nonlinear reverse current of the order of kA/m. The junction capacitance is extremely small due to the small junction area. The voltage sensitivities of the GNR-based backward diode as a function of frequency are shown in Fig. 4. The diode can have a much better sensitivity for terahertz wave than a GaAsSb/InAlAs/InGaAs heterojunction diode [5].

We try to form GNRs having various widths and edge-terminations using a bottom-up approach [6]. In fact, we used a precursor shown in Fig. 5 (HFH-DBTA), aiming at synthesizing partially F-terminated AGNRs. The F atoms at the edges, however, were detached during the cyclodehydrogenation of partially-edge-fluorinated polyanthrilyenes 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 polyanthrilyene, plays a crucial role in significantly lowering the activation energy of carbon-fluorine bond dissociation.

Incidentally, we have found that locally aligned GNRs are obtained when we use these precursors, as shown in Fig.6. Simulations show that this alignment is related to the relative strengths of precursor-precursor and precursor-substrate interactions. We have also fabricated a transistor using aligned GNRs as a channel. Transfer characteristics of the transistor are also described in the presentation.

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References

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- [6] H. Hayashi, et al., ACS Nano, 11, 6204 (2017).

Figures

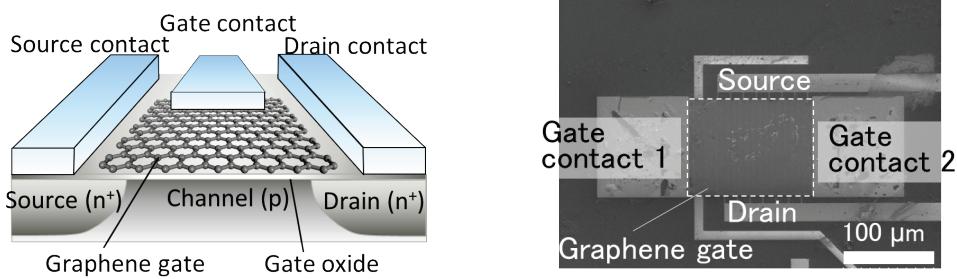


Figure 1: Schematic illustration (left) and scanning electron microscope image (right) of a gas sensor based on a graphene-gate transistor

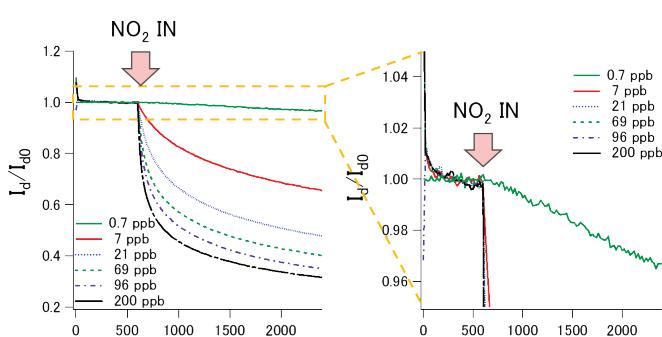


Figure 2: Dependence of the response (normalized drain current, I_d/I_{d0}) of a graphene-gate sensor on NO_2 concentrations.

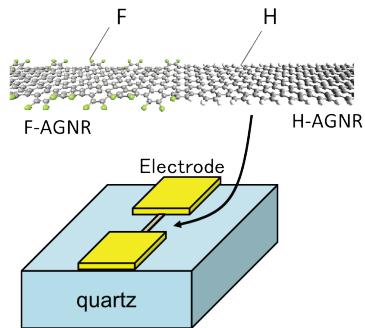


Figure 3: Schematic illustration of a diode using a heterojunction of F-AGNR and H-AGNR.

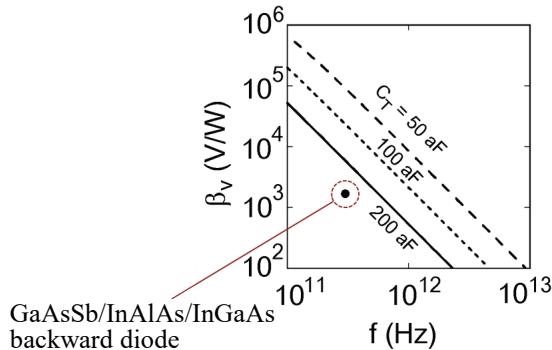


Figure 4: Calculated voltage sensitivity of a GNR backward diode, β_v , as a function of frequency with the total capacitance, C_T , as a parameter. The closed circle indicates β_v of a GaAsSb/InAlAs/InGaAs diode in Ref. 5.

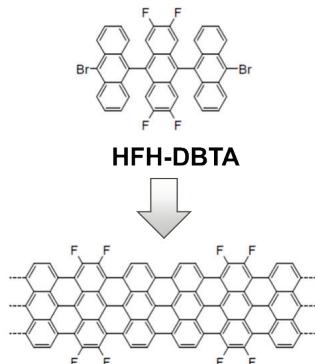


Figure 5: New precursor (above; HFH-DBTA)) for synthesizing a partially F-terminated AGNR (below)

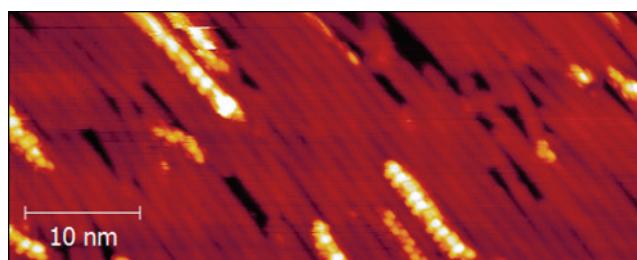


Figure 6: Locally-aligned AGNRs obtained from HFH-DBTA precursors.