OPERANDO ANALYSIS OF GRAPHENE DEVICE BY USING 3D NANO-ESCA
(I) –GATE-BIAS MODULATION OF CHARGE TRANSFER REGION AND ITS RELATION WITH DEVICE CHARACTERISTICS -

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We have used 3D nano-ESCA as the powerful means in material designation [1] and device fabrication [2, 3]. For the material designation, the 3D nano-ESCA in fact enabled us to characterize modulated chemical and electronic states of graphene due to the faceting of SiC thin films on 3D-microstructured Si(100) substrates [1].

In parallel with the material designation, we have studied graphene-based transistors [2,3]. As the first step, we have succeeded in observing a transistor using graphene as a channel, and the charge transfer region between graphene and metal contact was clearly observed. Unfortunately, however, this observation was carried out without gate bias application. Therefore, there is a gap between this observation condition and real operation conditions. To bridge a gap, it is needed to carry out the 3D nano-ESCA observation under operation condition, i. e. gate-bias application condition.

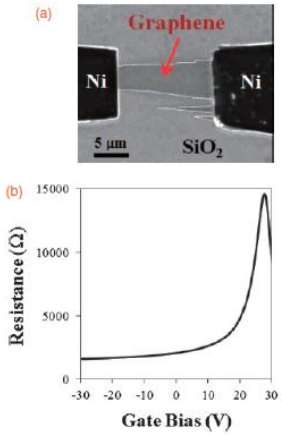

Figure 1 Optical micrograph (a) and Resistance-Gate bias curve (b) of the graphene transistor.

For the operando analysis of graphene transistors, the 3D nano ESCA installed at BL07LSU of SPring-8 was utilized, whose lateral resolution is below 70 nm [7]. In the transistors, exfoliated graphene and Ni thin films were used as the channel and metal electrodes, respectively. The Si substrate with SiO_2 thin film (90 nm) was used as the back gate. In this work, the Si substrate was used as a back gate to apply the gate bias, while graphene and metal electrodes were grounded.

The graphene transistor was imaged by mapping C1s and Si 2p intensity with 3D nano-ESCA, as shown in Fig. 2. The elemental mapping visualizes the graphene transistor more clearly, compared to the optical micrograph (Fig. 1(a)). Thus we are ready to carry out the pinpoint 3D nano-ESCA measurements at desired points.

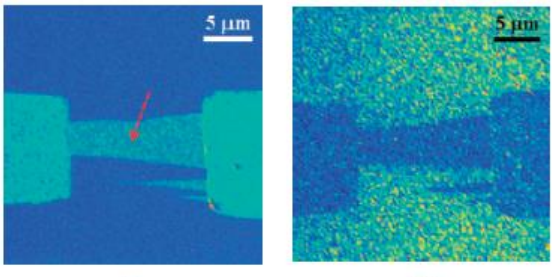

Figure 2 Core level intensity mapping of C 1s (a) and Si 2p (b) of the graphene transistor.

Here we show the pinpoint observation of C 1s core level at the center of the graphene channel (red arrow in Fig. 2(a)) (Fig. 3). The core

level spectra with the different gate bias (Fig. 3a) clearly demonstrate the shift of the graphene peak is due to the application of the gate bias.

For the quantitative analysis, the binding energy of the graphene peak is plotted against the gate bias (Fig. 3(b)). Assuming the ideal 2D system of linear band dispersion of the monolayer graphene with respect to the wave vector and using the simple capacitance model, the binding energy of graphene ($E_{BE}(G)$) which is doped by the electric field-effect is expressed as

$$E_{BE}(G) = E_{BE}(DP) - 6.0 \times 10^{-2}\sqrt{V_{CNP} - V_g} \ \text{(eV)} \qquad (2)$$

where $E_{BE}(DP)$ are the binding energies of graphene when the Fermi level coincides with the Dirac point, i.e., the energy difference between E_{DP} and the C 1s core level of neutral graphene. The curve fit to the experimental data, indicated by the dashed line in Fig. 3(b), was performed using eq. (3). Based on the curve fit results, V_{CNP} and $E_{BE}(DP)$ are estimated to be 28 V and 284.0 eV, respectively. The estimated value of V_{CNP} agrees well with that determined experimentally from the R–V_g characteristic (Fig. 2(b)). The estimated value of $E_{BE}(DP)$ is very close to the binding energy of neutral graphite (284.4 eV), which is considered to be close to that of neutral graphene.[31] The slight difference between these values may be ascribable to minute uncertainties in the incident photon energy or Fermi-edge measurements used to determine the binding energies. It is thus demonstrated by this simulation that our pinpoint operando photoelectron nanospectroscopy definitely observes the E_F shift of the graphene channel induced by the gate bias, in accordance with the linear band dispersion.

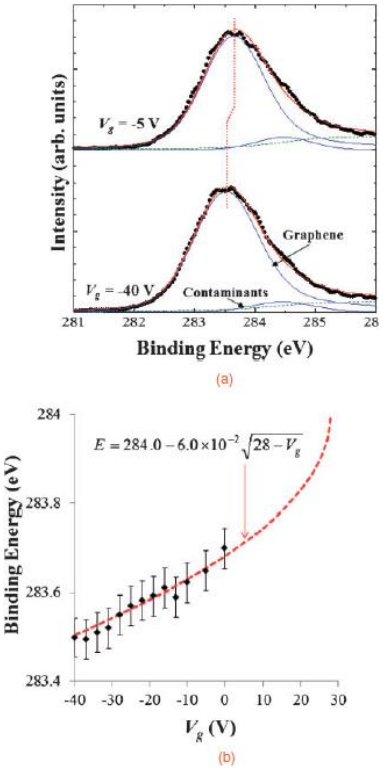

Figure 3 (a) Change of the C 1s core level spectra by the gate bias. (b) Dependence of the binding energy of the graphene peak on the gate bias.

The success of this operando observation extends our research into NEDO project with Sumitomo Electric Industries which includes all the factors, such as material designation, device fabrication, and operando observation of high-frequency (> 600 GHz) graphene-based transistors.

REFERENCES

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