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Definite Observation of Interfacial Charge Transfer in Graphene Transistor by Using Soft X-ray 3D Scanning Photoelectron Microscopy

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1. Introduction

Graphene can be the promising material for the next generation devices owing to novel physical properties, e.g. giant carrier mobility (>10^5cm^2/Vs). Graphene-based devices including field-effect transistor (FET) has been extensively studied to succeed the throne of Si in electronics.

The current status of device characteristics of graphene FET is, however, restrained from the ideal. One of the reasons for this is on the graphene-metal contact [2, 3]. Mechanistic understanding of the contact, i. e. charge transfer between graphene and metal, is therefore one of the focused issues in graphene device researches. For this purpose, spectromicroscopic studies have been performed. The techniques used in the previous studies, such as scanning photocurrent microscopy [4] and scanning gate microscopy [5] is, however, not adequate means because of the inability to remove the effect of surface carbon contaminations and perform depth-profile analysis.

In this study we have employed nanoscale 3D spatial distribution analysis using photoelectron spectroscopy (3D nano-ESCA) for the definite observation of the interfaces in graphene FET.

2. Experimental

3D nano-ESCA Observation

3D nano-ESCA is installed at BL07LSU of SPring-8 for the operando soft X-ray photoelectron spectroscopic analysis of advanced devices. The 3D nano-ESCA system is equipped with a focused X-ray probe and angle-resolved photoelectron spectrometer to realize highly-precise, nanoscale 3D spatial distribution analysis with the high precisions; subatomic layer resolution and 70 nm in surface normal and parallel directions, respectively, and the energy resolution of the spectra, E/ΔE exceeds 5000.

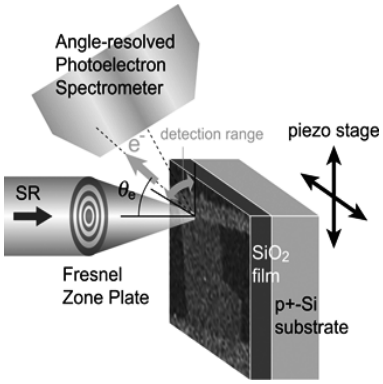

Fig. 1 Schematics of 3D nano-ESCA appratus

Sample Preparation

Exfoliated graphene from Kish graphite was transferred to SiO_2 thin film (90 nm in thickness) grown on p^+-Si(100) [3]. The surface of SiO_2 was made hydrophilic by the pretreatment described in the previous paper [6]. Ni electrodes for the graphene FET were fabricated by vacuum deposition .

3. Results and Dicusssions

Graphene Detection by C 1s spectra

Figure 1 shows a typical C 1*s* core level spectrum of the monolayer graphene. The C 1*s* peak is clearly decomposed into two components, the monolayer graphene (I) and surface contamination (II). In the observations documented below, the surface contamination is removed to do precise arguments.

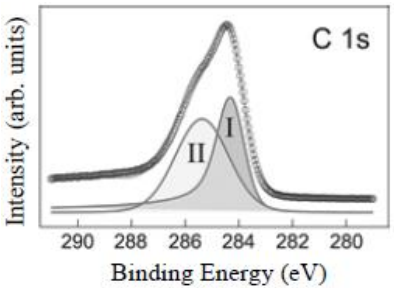

Figure 2 A typical C 1*s* spectra consisting of graphene (I) and contamination (II) components.

Spatial Distinction of the Graphene Transistor

Figure 2 compares an optical micrographs and a 3D nano-ESCA image of the transistor using monolayer graphene as a channel, Ni electrodes and SiO_2 as the gate insulator. In the center of the micrograph, the monolayer graphene is visible owing to the interference effect [7]. In the 3D nano-ESCA image, the C 1*s* of the monolayer graphene, Ni 3*p* of the Ni electrodes, and Si 2*p* of the SiO_2 thin film are spatially resolved. This image accords with the optical micrograph. We thus demonstrate that 3D nano-ESCA is adequate for the nanoscale analysis of graphene FET.

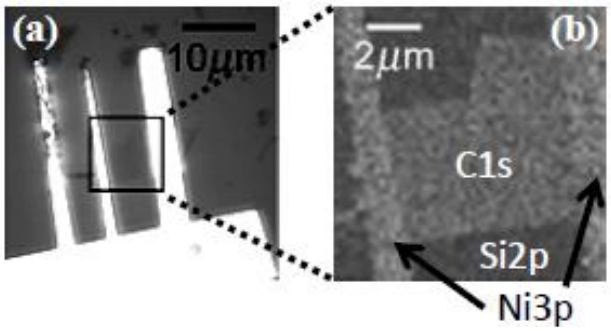

Figure 3 (a) Optical micrograph and (b) 3D nano-ESCA elemental mapping image of monolayer graphene FET.

Observation of the Graphene-Metal Interface

To definitely image the charge transfer region near the graphene-metal interface, the line profile of the binding energy of the C 1*s* peak across the graphene-Ni electrode interface is displayed in Fig. 3. For this line profile, the focused light probe is scanned along the dashed line in the 3D nano-ESCA image in the inset. This result clearly demonstrates the existence of the charge transfer region characterized by the energy shift of ~ 70 meV and the width of ~ 500 nm.

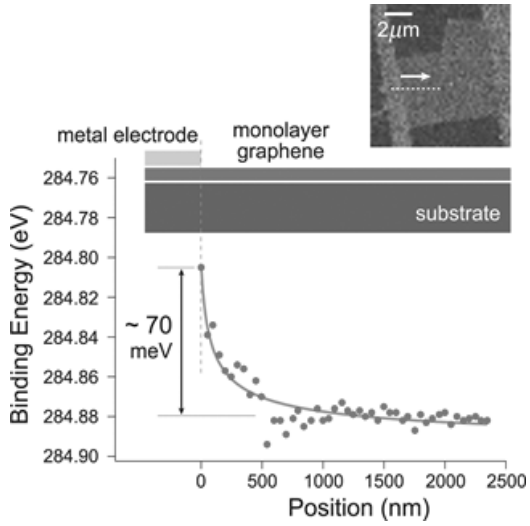

Figure 4 Line profile of the C1*s* peak position of the graphene peak, across the graphene-metal interface, as depicted in the dashed line in the 3D nano-ESCA image in the inset. The thin line expresses the fitting curve as described in the text.

The charge transfer region can be theroretically examined in terms of charge screening within the framework of Thomas-Fermi approximation, as suggested by Khomyakov et al. [8]. According to their calculation, the spatial variation of electrostatic potential induced in graphene near the interface is expressed by

$$V(x) \approx \frac{\Delta E}{\left(\sqrt{x/l_s} + 0.803\right)^{1/2}\left(x/l_s + 1.194\right)^{1/4}} \bullet\bullet\bullet (1)$$

for undoped graphene, where ΔE is the boundary potential constant derived from the work functions. $l_s = 0.081 \times \kappa / \Delta E$ (nm) indicates a scaling length, where κ is an effective dielectric constant in a graphene device structure. ΔE, κ, and l_s are estimated 0.31 eV, ~16, 4.2 nm, respectively by curve fitting using equation (1).

The value of κ thus obtained is larger than the reported value ($\kappa \sim 2.5$) estimated by averaging static dielectric constants of SiO_2 and vacuum. This deviation of κ may be explained by either the polarization inside the graphene or polar Si-OH groups in between graphene and the base SiO_2. This issue about the graphene-SiO_2 interface is being solved by the pinpoint 3D analysis employing the precise measurement of photoemission angle dependence [9].

4. Conclusions

Definite observation of the graphene device interfaces is realized by 3D nano-ESCA. Our study can serve a wealth of information on graphene device mechanism as well as basic physics, e.g. screening (many body effects) behind the device operation.

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