Complementary use of soft X-ray operando spectromicroscopies on the developments of next-generation devices

The developments of next-generation devices, such as 2D electron systems that includes AlGaN/GaN and graphene, is becoming increasingly important to supplement device functions of Si-based electronics, which have already reached the 15-nm design rules. Graphene has been extensively studied as a next-generation device material owing to its suppression of short-channel effects, which are desirable to reduce device size and its excellent electronic properties, such as giant carrier mobilities and the absence of diminished backscattering.

We have conducted research on graphene from wafer-scale growth [1] to transistor fabrication [2], and obtained a world-record high-frequency characteristic for graphene transistors (GFET) [2]. It is, however, inferred that parasitic resistances, such as the contact or access resistance, considerably degrade device performance [2]. The interfaces related with the parasitic resistances are responsible for the degradation. Furthermore, the impact of the interfaces on the device performances varies with the operation conditions, e.g., gate bias (Fermi level (E_F)), which makes GFET designation difficult. Because the development of the next-generation devices requires microscopic information on the electronic states near the interfaces under operational conditions, we have adopted operando spectromicroscopy to bridge the gap between the material and the device (Fig. 1).

Here we demonstrate how the complementary use of soft X-ray spectromicroscopies, 3D scanning photoelectron microscopy (3D nano-ESCA) at **BL07LSU** [3], and photoemission electron microscopy (PEEM) at **BL17SU** [4] is powerful tool to probe the electronic states, i.e., both conduction and valence bands of GFET, under operational conditions. One of our main targets is the interface between graphene and SiO_2 because channel-gate oxide interfaces are at the heart of field-effect. In addition, the interface between graphene and a metal contact is crucial because the contact resistance contributes non-negligibly to a low channel resistance.

To examine the validity of operando 3D nano-ESCA for the interface with gate oxide, the shift of E_F at the center of the graphene channel by the gate bias application was examined in detail by pinpoint C 1*s* core level photoelectron spectroscopy (Fig. 2(a)) [3]. Qualitatively, the C 1*s* peak of graphene is red-shifted by a negative gate bias application, which lowers E_F. For further quantitative analysis, the data were reproduced by a theoretical curve based on a simple capacitance model and linear DOS (Fig. 2(b)). One of the extracted parameters, the gate bias at the charge neutrality point, V_{CNP}, agrees with that extracted from the macroscopic drain current — gate bias curve. The value of another extracted parameter, E_{BE}(DP), which is the binding energy of an electrically neutral graphene channel, is consistent with the binding energy of electrically-neutral graphite. Thus, the field-effect of GFET is probed directly by operando 3D nano-ESCA.

The change in the conduction bands of GFET under a gate-bias application was investigated with microscopic X-ray absorption spectroscopy (μ-XAS) by collecting Auger-electron images near the C 1*s* absorption edge [4]. The μ-XAS spectra at the center of the GFET channel is changed by the gate-bias application (Fig. 2(c)). The π* peak change indicates that the DOS in the conduction band is altered. This observation cannot be explained within the framework of the so-called initial-state approximation. Instead, the final-state is responsible for the spectral change. More specifically, many-body effects due to core holes, i.e., the excitonic effect and Anderson orthogonality catastrophe, modify the π* peak lineshape. The degree of the many-body effect depends on the density of states near E_F. Thus, operando PEEM through μ-XAS

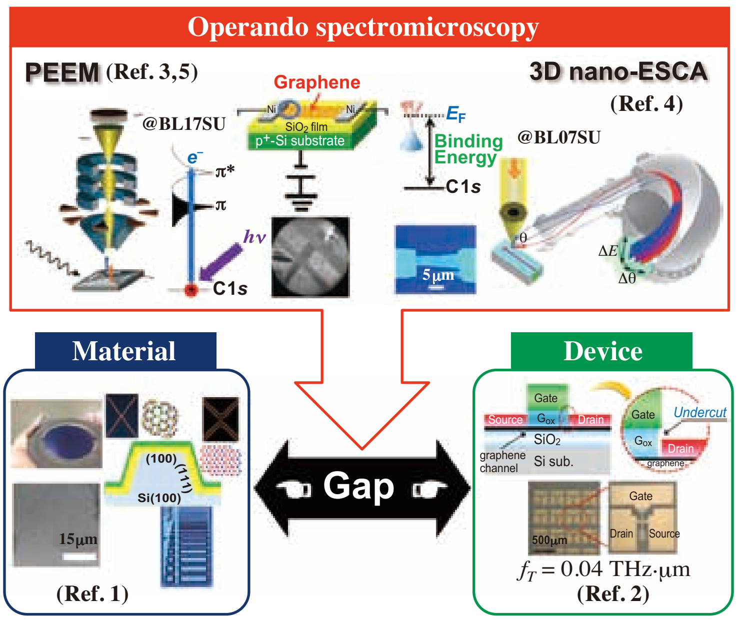

Fig. 1. Role of operando spectromicroscopy.

can probe microscopic information in the conduction bands and E_F.

The presence of a charge transfer region (CTR) near the metal contact is a serious issue in developing high-performance GFET. The CTR is speculated to be wide (< 1 μm) due to the vanishing DOS near the Dirac point, which makes analysis of the contact resistance difficult [5]. The CTR was investigated by 3D nano-ESCA (Fig. 3(a)) [5]. The binding energy of graphene is reduced near the metal contact. This indicates that the electron transfer from graphene to the contact metal spans a wide region (~1 μm) and provides evidence for the presence of the CTR.

The CTR was investigated in more detail by operando PEEM (Fig. 3(b)) [4]. Consistent with 3D nano-ESCA, the existence of the CTR is inferred from the π* peak change which reflects the E_F change. More interestingly, it is clarified that the gate bias application narrows the width of the CTR. This can be explained by considering the fact that additional carrier doping by the gate bias reduces the screening length in the CTR.

In summary, the complementary use of soft X-ray operando spectromicroscopies reveals local variations in the electronic states near device interfaces, which cannot be elucidated from device simulations and consequently be considered in device design. The significance of the operando spectromicroscopy is now recognized, and has resulted in its adoption as a target in the NEDO academic-industrial alliance project with Sumitomo Electric Industries.

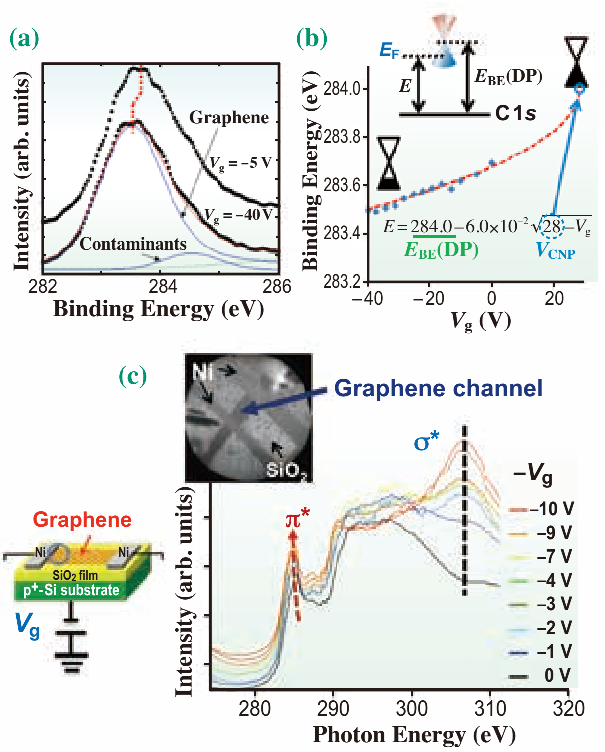

Fig. 2. Operando observations of field-effect by **(a, b)** 3D nano-ESCA [3] and **(c)** PEEM [4]. Blue rhombi and red dotted line in **(b)** are experimental data and the fitted curve, respectively.

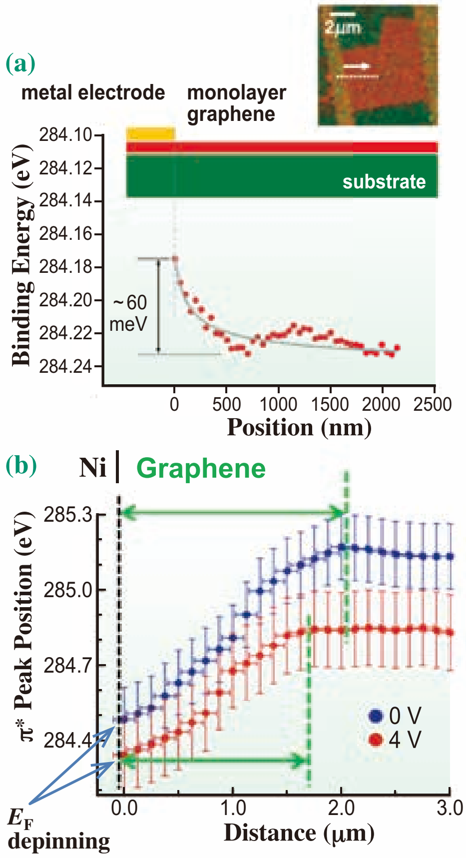

Fig. 3. Observation of metal contact by **(a)** 3D nano-ESCA [5] and **(b)** operando PEEM [4].

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