Operando Spectromicroscopy for Nano-layer Devices: Chemical Potential Shift in Organic Field Effect Transistors

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With advance in miniaturization of devices, nano-scale spatial analysis has become more important to characterize device properties. Scanning Photoelectron Microscopy (SPEM) is one of the most powerful imaging techniques for investigating the local electronic and chemical bonding states in solid materials. Then we have developed a SPEM system with a nondestructive depth profiling analysis capability for 3D spatially resolved electron spectroscopy for chemical analysis (ESCA) using an angle-resolved photoelectron spectrometer, called "3D nano-ESCA" [1]. Using this system, we have succeeded in direct measurements of limiting factors for high-performance in devices such as the interfacial charge transfer region in Graphene field effect transistors (FETs) [2], the conductive paths in nanowire resistance randam access memory (ReRAM) devices [3], and the lithiation process in cathode nano particles for Li-ion batteries [4].

Figure 1. New sample holder for *operando* analysis (left) and actual condition of the 3D nano-ESCA measurements (right). The semiconductor parameter analyzer is shown in a red circle.

In the next step, we aimed to realize nano-spot spectroscopy under device operation, so-called *operando* analysis, using our 3D nano-ESCA in order to examine dynamics of reactions and carrier flows in practical devices. Then we have introduced a new sample holder with five terminals for voltage induction and a semiconductor parameter analyzer in the measurement system as shown in Fig. 1.

Here we demonstrate a SPEM observation of organic field effect transistors (OFETs) using the 3D nano-ESCA which enables to probe the pin-point local electronic states at the channel region under device operation.

OFETs are one of the promising candidates for applications with low environmental load, low-cost, light-weight, and flexibility. Highly single-crystalline organic films with high carrier density of ~10 cm^2/Vs utilized as a transistor channel can be obtained by a simple solution process. In order to clarify the fundamental mechanism of energy alignment inside the OFET device with complicated interfaces, we have carried out pin-point *operando* analysis and potential distribution mappings through a synchrotron radiation (SR) soft X-ray SPEM using the 3D nano-ESCA

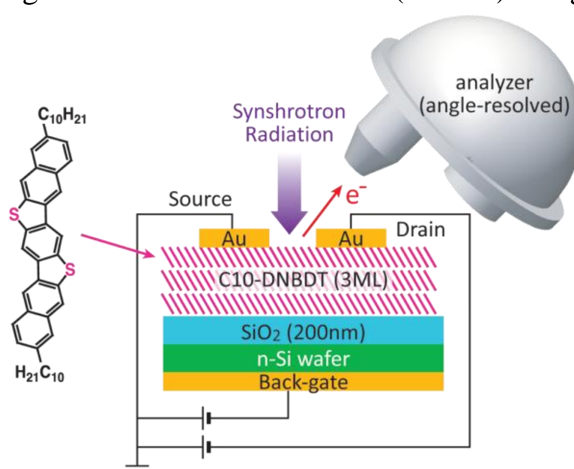

Figure 2. Molecular structure of C10-DNBDT and schematic image of SPEM analysis of OFETs using 3D nano-ESCA .

system at the University-of-Tokyo Materials Science Outstation beamline, BL07LSU, at SPring-8.

We employed a new organic semiconductor material, 3,11-didecyldinaphtho[2,3-d:2',3'-d'] benzo[1,2-b:4,5-b']dithiophene [C10-DNBDT; Fig. 2]. The C10-DNBDT thin films with thickness of ~10 nm (2-3 monolayers; ML) were prepared on 200 nm thick SiO_2 films on Si substrates by a modified edge-casting solution-crystallization technique [5]. Au electrodes were fabricated by vacuum deposition followed by photolithography and etching techniques. The following results were all taken at the excitation photon energy of 1000 eV.

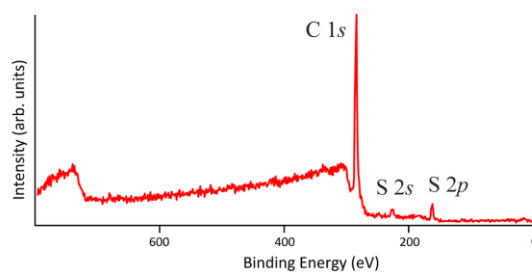

Figure 3. Wide range photoemission spectra taken on the C-10 DNBDT film.

Figure 3 shows the wide range photoemission spectrum for the 3 ML C10-DNBDT plane film without FET structures. The C 1*s*, S 1*s*, S 2*p* core level peaks are clearly detected. Then a pin-point photoemission spectroscopy under biasing at the backgate was performed to plot the line-profile for the binding energy (BE) of the C 1s core level peak, which is the largest component in Fig. 3 owing to the C10-DNBDT molecule. The energy peak shift of about 0.1 eV toward lower BE at the center of the organic film channel was clearly detected by applying -30 V to the backgate as shown in Fig. 4. The *p*-type doping from backgate electrodes induced by field effect was confirmed by the direct measurement of chemical potential shift corresponding to band bending using our *operando* SPEM analysis[6].

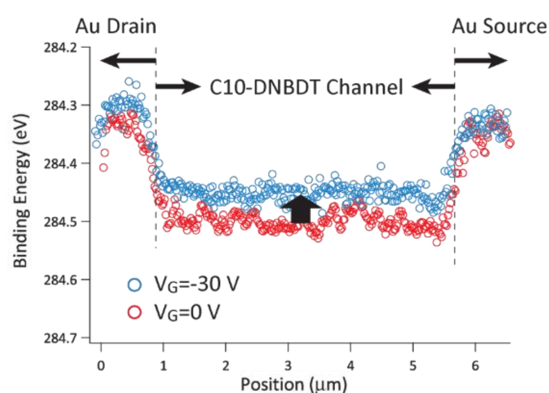

Figure 4. Line profile of the C 1*s* BE on the OFET structure.

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