Establishment of Method for Analyzing Next-Generation Metal-Oxide-Semiconductor Field-Effect Transistors

Nondestructive analysis of internal states of semiconductor laminated structures

Achievements

- SPring-8 synchrotron radiation has improved the detection sensitivity for internal property of a material by approximately fivefold compared with conventional **X-ray photoelectron spectroscopy.***
- For a laminated electrode/insulating-film/semiconductor structure, the relationship between the change in the photoelectron spectrum and the applied voltage has been clarified to calculate the voltage applied to the insulating film.
- An analysis technique that can be used to develop next-generation **metal-oxide-semiconductor field-effect transistors (MOSFETs)**** has been established.

R&D facility: Toshiba Corporation

***X-ray photoelectron spectroscopy** is a method of analyzing the elements of a sample surface and their electronic states by measuring the energy of photoelectrons emitted upon X-ray irradiation of the sample. The depth to which the sample can be analyzed depends on the energy of the irradiated X-rays. In laboratories, soft X-rays such as Al-Kα (1.4867 keV) are used. In contrast, at SPring-8, synchrotron radiation hard X-rays with an energy of 4-10 keV are used, enabling the analysis of samples at a greater depth. This method of using hard X-rays is called **hard X-ray photoelectron spectroscopy (HAXPES)**. Most of the measurement and analysis techniques used for soft X-ray photoelectron spectroscopy and HAXPES are the same; only the energy of the X-rays is different.

****A metal-oxide-semiconductor field-effect transistor (MOSFET)** is a field-effect transistor that controls the current between the source and drain by applying different voltages to the gate electrode. A laminated structure consisting of a metal (as the gate electrode between the source and drain), an oxide (as a gate-insulating film), and a semiconductor (a silicon substrate) is adopted in a MOSFET. Many current large-scale integrated circuits (LSIs) adopt a MOSFET structure.

Role of SPring-8

Background

With the aim of developing next-generation MOSFETs, the introduction of new devices, such as ferroelectric gate-insulating films and metal gate electrodes, and the fabrication of multilayered insulating films have been examined. Therefore, methods of analyzing such new materials and their inner structure should be established.

Conventionally, X-ray photoelectron spectroscopy has been used for such analysis; however, only the surface of a sample can be observed with this method, and the inner structure of a sample cannot be observed without physically destroying the sample. In addition, it may not be possible to analyze spectra because the number of observable photoelectron peaks is small and the peaks of the spectra corresponding to different coexisting elements may interfere with each other. In some cases, satisfactory accuracy cannot be obtained due to the complicated shape of the peak spectrum.

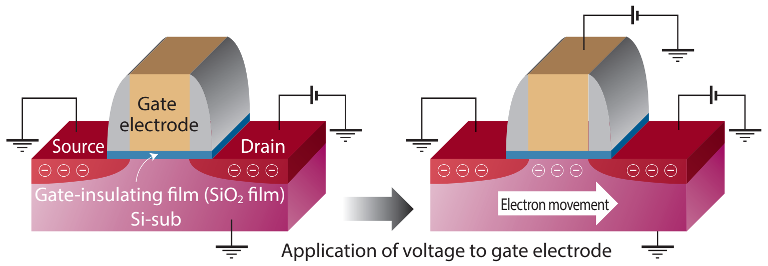
Results

In the case of HAXPES using intense SPring-8 synchrotron radiation, the depth of observation is as high as 20-30 nm and the number of observable photoelectron peaks is increased. Furthermore, optimum observation conditions were determined for the total reflection method, in which grazing incident X-rays are totally reflected on the sample surface, to obtain the distribution of elements in the depth direction by changing the observation depth with increased detection sensitivity.

In addition, the behavior of the photoelectron spectra was observed by changing the voltage in a stepwise manner to evaluate the potential distribution induced in the semiconductor laminated structure when a voltage is applied. The voltage applied to the insulating film was precisely determined. Using the results obtained, the development of next-generation MOSFETs is being carried out.

Structure and operation of MOSFET

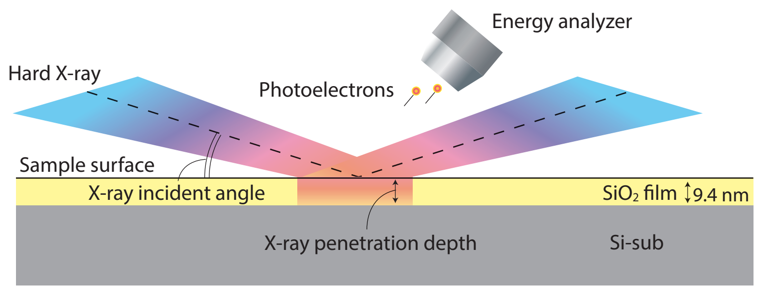
A MOSFET has a laminated structure in which a gate-insulating film is sandwiched between a silicon substrate (Si-sub) and a gate electrode. Silicon dioxide (SiO_2) is generally used for the gate-insulating film. When a voltage is applied to the gate electrode, carriers are generated immediately below the SiO_2 film to allow current to flow between the source and drain.



Total-reflection HAXPES

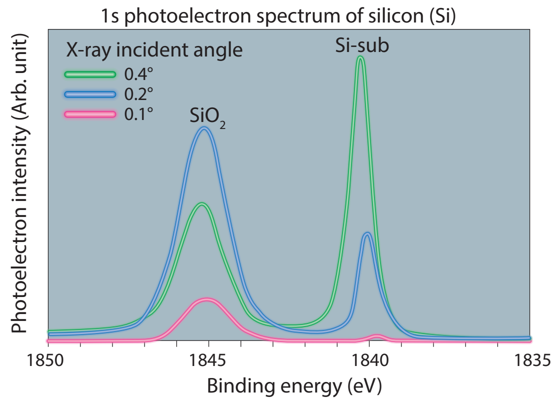
Total reflection is induced when X-rays are irradiated at a surface at a very small incident angle. Even in the case of total reflection, hard X-rays can penetrate into a sample to approximately several nanometers below the surface, thus efficiently exciting photoelectrons. The penetration depth can be varied by controlling the incident angle, meaning that the depth of the layer in which photoelectrons are excited can be changed.

To examine the increase in detection sensitivity and the change in penetration depth for the case of total reflection using HAXPES, a SiO_2 film was observed by this method.



Observation results of photoelectron spectra under total-reflection condition

When the incident angle of hard X-rays is 0.4°, the intensity of the photoelectron peak corresponding to a SiO_2 film on the surface side is smaller than that corresponding to the Si-sub, whereas when the incident angle is 0.2°, the relative intensities are reversed. When the incident angle is 0.1°, the peak corresponding to the Si-sub is negligible. From this result, it was found that the smaller the incident angle, the shallower the depth of observation using X-rays.



Measurement of photoelectron spectra under voltage application

With HAXPES, the measurement of photoelectron spectra with a voltage applied to the electrode is possible because a sample with a thick laminated structure can be observed nondestructively. The positions of the photoelectron peaks corresponding to each laminated layer were measured while applying a voltage to the sample with a gate stack structure. The results indicate that the relative shift of the photoelectron peak of each layer depends on the applied voltage and that the voltage applied to the insulating film depends on the polarity.