PRESS RELEASE

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High Energy Accelerator Research Organization (KEK)
Japan Science and Technology Agency (JST)

Successful visualization of the internal structure of semiconductor devices under operation

Proposal of a new method for evaluating semiconductors

Executive summary

●Question

The p-n junction interface, at which p-type and n-type semiconductors are bonded plays a central role in semiconductor devices. It was discovered about 70 years ago;however, up to date, the p-n junction interface has not been directly observed.

●Findings

By further developing the experimental setup created by Fukumoto (one of the authors of the manuscript) that can visualize conductive electrons in semiconductors, we succeeded in observing the real and energy-spaces of the charge-depleted region formed at the p-n junction interface.

●Meaning

This method enables the evaluation of semiconductor devices by direct visualization. It is applicable to all semiconductor devices, and hence is expected to contribute to the development of the semiconductor industry.

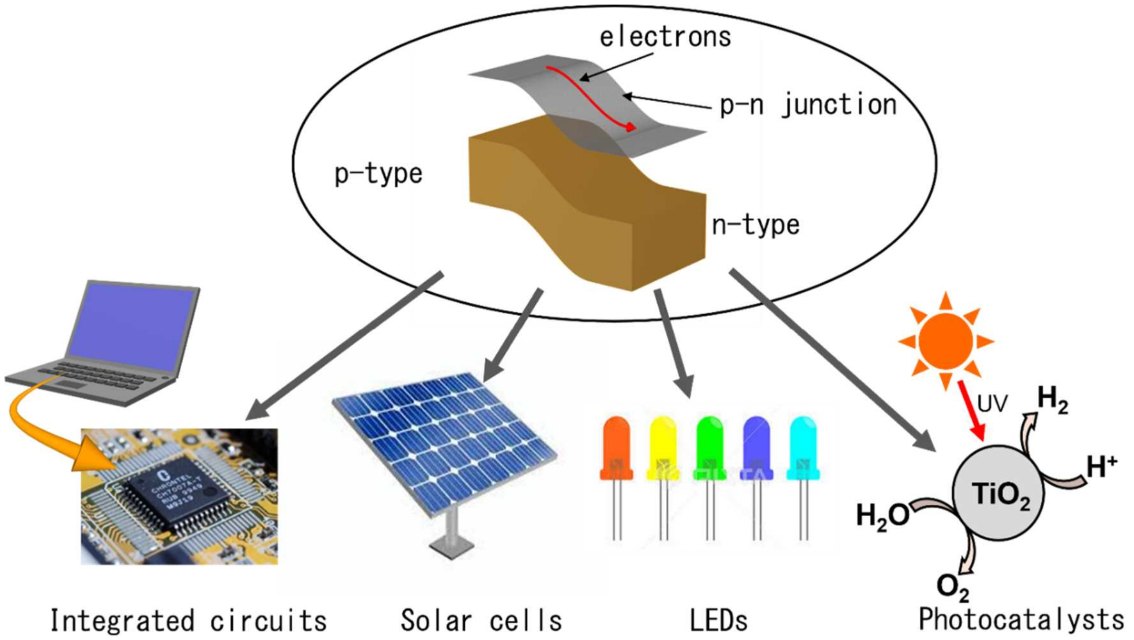

Figure 1 Semiconductor devices function by controlling the flow of electric current at the p-n junction formed at the interface between two types of semiconductors, p-type and n-type.

Summary

For the first time, researchers have succeeded in visualizing the mechanism that controls the flow of current in a tunnel diode (※1), a type of semiconductor device, in its operating environment. This method is expected to be applied to the performance evaluation and development of various semiconductor devices such as transistors and solar cells.

※1. A tunnel diode is a type of semiconductor diode that utilizes the quantum tunneling effect to allow current to flow in only one direction. Applying a reverse bias voltage causes a tunnel current to flow.

Overview

Using a photoemission electron microscope with a femtosecond pulsed laser light source (fs-PEEM) (※2) installed at the Institute of Materials Structure Science (IMSS), High Energy Accelerator Research Organization (KEK), we succeeded in imaging the shape of the depletion layer (※3), which is formed at the semiconductor p-n junction interface and plays an important role in controlling electric current, during device operation. This new method is expected to be used to characterize various semiconductor devices such as diodes, transistors, solar cells, and LEDs, as it can visualize the internal state of the device while evaluating its performance.

※2. fs-PEEM
A microscope in which the sample is irradiated by photons and the emitted photoelectrons are detected (Figure 2). By using an ultrashort pulse laser as the light source, the photon energy can be freely varied in the near-infrared, visible, and ultraviolet light ranges. This makes it possible to efficiently observe conductive electrons.

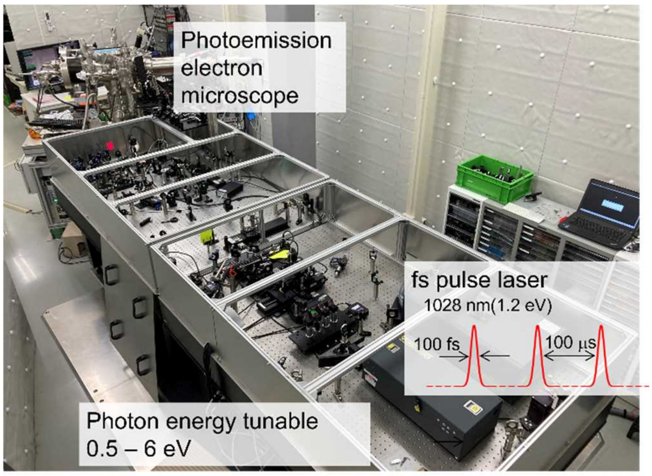

Figure 2. Photograph of the femtosecond (1 millionth of 1 billionth of a second) photoemission electron microscope (fs-PEEM).

The laser pulses are extremely short, with each pulse irradiating the sample for only 100 fs (1 femtosecond is one millionth of 1 billionth of a second), and a gap of 100 microseconds (1 microsecond is one millionth of a second) between the pulses.

※3. Depletion layer

When a p-type semiconductor and an n-type semiconductor are bonded, the energy levels at the interface are inclined so that the energy levels of the valence band of the p-type semiconductor, where holes are the majority charge carriers, and the conduction band of the n-type semiconductor, where electrons are the majority charge carriers are aligned. This creates a region (depletion layer) where electrons and holes do not exist. In a normal diode, when an external voltage is applied in the forward direction, the inclination becomes smaller and charges flow. In the reverse direction, the inclination becomes larger and no current flows. In a tunnel diode, electrons move from the valence band of the p-type semiconductor to the conduction band of the n-type semiconductor by applying a reverse bias voltage so that they tunnel through the depletion layer.

Research group

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Keiki Fukumoto – Associate Professor

A word from the researcher

KEK IMSS, Associate Professor Keiki Fukumoto

Our method enables us to directly visualize physical phenomena on the interfaces of semiconductors, in the form of images, to obtain additional information as a result. We aim to develop equipment that could lead to a paradigm shift in semiconductor research.

Why did you start this research?

In 1948, William Shockley discovered electrical rectification (diode), in which a current flows or does not flow when p-type and n-type semiconductors are bonded, depending on the polarity of the externally applied voltage. Since then, almost every semiconductor textbook has included a diagram of the energy structure of the depletion layer drawn by Shockley. However, this diagram is inferred from electrical measurements and theoretical calculations. To directly evaluate the performance of semiconductor devices, it is important to visualize the p-n junction interface, that is, to observe the cross section of the device. To achieve this, there were several challenges that had to be overcome. One of them was that when observing small samples of less than a millimeter size using a photoelectron microscope, the edge of the sample behaves as a structural defect and emits a huge number of photoelectrons. This makes it difficult to efficiently detect photoelectrons from the region of interest. Furthermore, the electric field generated from the edge of the sample distorts the photoelectron trajectory, resulting in a significant decrease in spatial resolution, which also complicates the measurement process. In this study, by observing the cross section of a semiconductor device under device operation, structural changes in the depletion layer formed at the p-n junction interface were clarified.

Where did the inspiration come from?

Around 2014, I accidentally discovered a method to image electrons moving inside semiconductors [Fukumoto et al., Applied Physics Letters 104, 053117 (2014)]. I came up with the idea that if we could see electrons, we might be able to see the depletion layer, where electrons no longer exist.

Where did you put in effort?

New discoveries require multiple measurements to confirm, using several methods. In time-consuming experiments, confirming reproducibility is a difficult task. In order to enable repeated measurements, we carefully created programs to operate the experimental equipment, as well as programs to analyze the enormous amounts of images acquired, and built an environment that allows experiments to be performed easily. This is the result of gradually improving the equipment over the last 10 years or so.

What did you find?

The p-n junction interface is the heart of a semiconductor device, and the depletion layer formed at the interface changes shape when an external voltage is applied, acting as a valve to control the flow of electric current. In this study, using a photoelectron microscope with a pulsed laser as a light source, we were able to directly visualize the p-n junction in a tunnel diode, a type of semiconductor device (Figure 3). We demonstrated that it is possible to image the change in the depletion layer structure at the p-n junction interface, as well as the tunnel current, under device operation. This method can be applied to a variety of semiconductor devices and is expected to contribute to future device development.

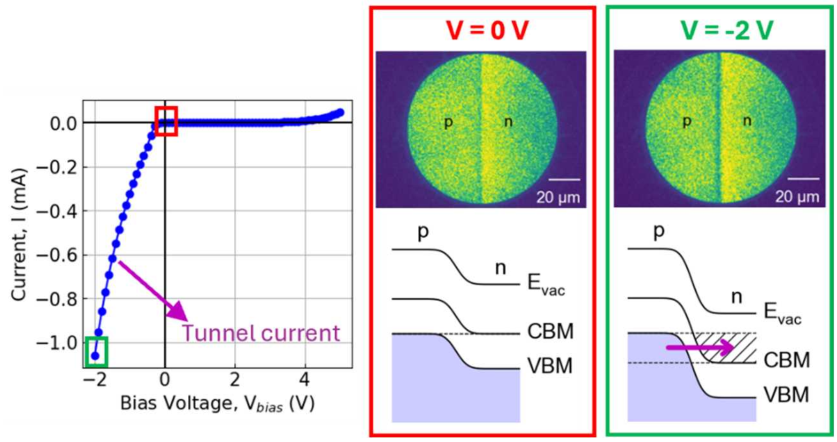

Figure 3 (left) current-voltage curve of a tunnel diode. (center and right) photoelectron microscope images and energy levels depending on the applied voltage. A color scale is applied to the images. The depletion layer can be seen at the middle of the images, between the p-type region (left), and n-type region (right), with its width widening at V= -2V. Furthermore, energy spectra were acquired simultaneously, from which it was observed that at V= -2V, the energy levels of the n-type semiconductor shifted downwards and that a tunnel current flows as a result.

So how will the world change?

The depletion layer plays a central role not only in the tunnel diode measured in this study, but in most semiconductor devices. As a new method for evaluating semiconductor devices, this technique is expected to find applications in a wide range of semiconductor industries. In addition, direct observation of the depletion layer inside a device is expected to improve the efficiency of the design and development of new materials and devices, contributing to the realization of next-generation high-performance semiconductor devices.

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

Acknowledgements

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Paper Information

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