Developing terahertz light sources through semiconductors with nanostructures

Masahiro Asada
(Professor, Tokyo Institute of Technology)
Industry-Academia Collaborative R&D Program
Creation of innovative fundamental technology to pioneer the new era of terahertz waves
Research Leader, Research on ultra-compact, high-efficiency room-temperature terahertz oscillators through resonant tunneling diodes (2011-2015)

Attempts to overcome the terahertz gap

The frequencies around 1THz, which lie midway between radio waves and light, are known as the terahertz band (or sub-millimeter wavebands, far-infrared). This has been an area of research that has not been explored until now. Light sources and detectors in semiconductor devices that are able to generate terahertz waves have not been fully developed. Among researchers, this is also described as the “terahertz gap.”

In recent years, it has become clear that the light sources for this frequency band can be applied to a very wide range of fields, including ultra-high-speed communications, information processing, imaging, spectroscopic analysis, and measurement. As a result, research in this area has begun to flourish. The development of light sources for the terahertz frequency band is becoming one of the key focuses of the industrial sector.

JST has implemented the Industry-Academia Collaborative R&D Program to promote fundamental research through universities, etc. that contribute to solving the technical challenges that are shared across the industrial sector. Within this program, Professor Masahiro Asada has produced significant results in the development of light sources for the terahertz frequency band. Using resonant tunneling diodes, which is a semiconductor device, he has succeeded in producing 1.92THz waves.

The periphery of the 1THz frequency is a valley without satisfactory light sources, and is known as the “terahertz gap.” Currently, resonant tunneling diodes are the only things that can generate frequencies exceeding 1THz independently at room temperature, and there are high expectations for these diodes as elements with the potential for closing the terahertz gap.
Success in developing room-temperature terahertz oscillators using resonant tunneling diodes

Producing semiconductors with microstructures in nanometer order is considered to be one of the more powerful methods for bringing about the realization of high-performance light sources and detectors in the terahertz band. In addition to significantly reducing the traveling time of electrons, it can also draw out new electron properties that are generated through the nanostructure.

Professor Asada and his team have been driving forward their research in pursuit of discovering new phenomena in semiconductor nanostructures in relation to terahertz waves, with the aim of creating high-performance terahertz oscillators and detection devices through nanostructures. Using resonant tunneling diodes, one of the semiconductor elements of nanostructures, they have succeeded in developing room-temperature terahertz oscillators for the first time among electronic devices. However, as the output is still small, research is ongoing with the aim of increasing output and creating oscillations at even higher frequencies.

Apart from this, Professor Asada and his team are also engaged in research to create new terahertz devices, including terahertz detection devices and the related integrated circuits. If it becomes possible to use terahertz waves, it should be possible to achieve ultra-high-speed wireless communications at several tens to several hundreds of gigabits per second. With the aim of achieving such wireless communication applications, they have also undertaken research on terahertz modulation elements based on new principles, and devices that integrate such elements.

Room-temperature terahertz basic wave oscillation developed through resonant tunneling diodes, a first among electronic devices. Left shows the device structure. Right shows the oscillation spectrum.

Numerous achievements ranging from high-frequency high-output developments, to wireless transmission

Professor Asada and his team have produced numerous achievements through the development of terahertz light sources. The first is their success in increasing frequency. They have produced a micro-slot antenna, which is a type of antenna used for wireless communications; they have also produced a compact terahertz oscillator that integrates resonant tunneling diodes. Through these developments, they have reduced the electron delay of resonant tunneling diodes and reduced antenna loss, and succeeded in achieving room-temperature oscillation at 1.92 THz, the highest frequency among semiconductor electronic devices. Furthermore, by optimizing the antenna structure, they have also increased output to 0.61 mW at 0.62 THz, for example, obtaining the highest output for single oscillators at this frequency band.

They have also developed oscillators that do not require silicon hemispherical lenses. Silicon hemispherical lenses, which have been used in techniques to date, have a high level of directivity; however, they also have many disadvantages, such as their large size, that they require optical axis adjustments, and that they produce loss on the surface. In contrast, by proposing and producing oscillators that integrate antennas and do not require the installation of silicon lenses, the team has potentially achieved improvements in directivity and output.

They have also succeeded in producing variability in frequencies. By integrating varactor diodes, which are a type of diode with variable capacitance values, into resonant tunneling diode oscillators, they succeeded in producing an oscillator that enables electrical changes in frequencies. This oscillator draws out frequencies of 0.78 – 0.9 THz for single elements, and 0.58 – 0.9 THz for four-element integrated arrays. This element was successfully applied to the measurement of the absorption spectrum of organic matter. In addition, multi-element integrated arrays also enable the development of an ultra-compact integrated chip for spectroscopic analysis, with a wide variable range of more than 1 THz.

They have also formulated the structure of resonant tunneling diode oscillators that allow for high-speed direct modulation of output, and obtained high-speed modulation up to 30 GHz through modulation of the bias. This property is useful for various measurements and in high-speed communications. One of the applications that the team has succeeded in is the wireless transmission of 30 Gbps.
Towards the development of key devices in the terahertz field

The advantages that resonant tunneling diodes have are their compact size, and their ability to function at room temperature. The advantage of terahertz waves lies in the 0.8 – 2.4THz band, where there is a balance between substance permeability and the presence of a fingerprint spectrum for identifying substances. In social implementation, terahertz wave technology achieved through the use of resonant tunneling diodes is anticipated to fulfill many purposes, including use for conducting checks on suspicious items at airports.

Professor Asada and his team continue to aim for the realization of an ultra-compact, high-efficiency light source that can become a key device in various applications of terahertz waves.

Going forward, they aim to contribute to the field of terahertz development through the optimization of resonant tunneling diodes and antenna structures, including the realization of oscillations that exceed 2THz frequency and 1mW output, ultra-compact, high-directivity oscillators that do not use silicon lenses, as well as the development of application to an expansion in the variable range for elements with variable frequencies, composition of spectroscopic analysis chips, and high-performance oscillators with high-speed direct modulation of high frequencies (~ 100GHz).