Appendix

This paper describes graphene plasmons and the background of this research in more detail.

1. What is Graphene Plasmon?

Plasmons are plasma oscillations of charge density in solids, and plasmonics using the confinement of electromagnetic fields in nanoscale below the diffraction limit has been applied in various fields (for details, refer to *NTT Technical Journal*[1]). Such plasmonics were originally developed using metallic materials. However, metal based plasmonics has unavoidable problems, such as significant loss and poor controllability, and the range of applications is currently limited. Plasmons in graphene are attracting attention as a potential solution to these problems.

Graphene plasmons have the following advantages in the terahertz (THz) to mid-infrared region: (1) phase and amplitude can be dynamically controlled by modulating the charge density, (2) propagation over long distances (approximately 50 wavelengths in theory) are possible due to low loss, and (3) wavelength can be compressed approximately 300 times compared to free space. By taking full advantage of these points, we expect to construct plasmonic circuits that can electrically control high-frequency signals above THz in nanoscale (for details, refer to *NTT Technical Journal*[2]).

2. Conventional methods for measuring graphene plasmons

To realize the promising application of graphene plasmons to THz circuits, it is necessary to generate dynamically controlled plasmons at a certain point A in the THz range, to control the propagation on the circuit, and to detect the phase and amplitude of the propagated signal at a remote point B. However, previous studies on graphene plasmons have failed to satisfy the conditions required for this circuit operation.

Until now, studies on graphene plasmons in the THz region have used a technique to excite plasmons using THz light propagating in free space. In these methods, to convert THz light into graphene plasmon, a designed structure is built into the graphene sample[3], or a near-field scanning optical microscope [4] is used. However, due to experimental limitations, the conversion efficiency between THz light and plasmon is low, and the measurement is limited to detect static plasmon standing wave, so the conditions necessary for the circuit operation described above cannot be satisfied.

On the other hand, it is known that graphene plasmon can be excited using electrical pulses, and NTT has been conducting research to realize graphene plasmon circuits[5, 6]. However, measurement of graphene plasmons in the THz region has not been possible because the bandwidth of conventional electronics has limited to the GHz region. In this research, we developed new THz electronics technology[7, 8] that can generate and detect high-frequency current in the THz region. Furthermore, by integrating graphene devices on the same chip, we succeeded in achieving electrical generation, propagation control, and detection of graphene plasmon wave packets in the THz region for the first time (Table 1).

	Conventional Optical Measurement	Conventional Electrical Measurement	This Research
THz Region	○	×	○
Operation Circuit	×	○	○

Table 1 Research Positioning

3. References

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