Femtosecond Laser Fabricated Moth-eye Structures for Antireflection in Terahertz Region

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論文内容の要旨

Terahertz (THz) radiation (0.1–10 THz) has been researched for applications in a wide range of fields, including communications, security, food inspection, and biomedical diagnosis. Due to the high refractive index of materials commonly used for THz components, a non-negligible part of the power will be reflected at the interface when the THz waves propagating from air to the components. This undesired high reflection loss is hindering the applications of THz technologies. Hence, reducing reflection loss is a key aspect of improving the performance of THz systems and promoting the applications of such THz technologies.

Subwavelength surface-relief structures, also known as moth-eye structures, can be used to reduce reflection loss over a broad frequency band. Benefitting from the simplicity, processing efficiency, and flexibility, ultrafast laser processing was employed to fabricated moth-eye structures on actual THz applications, such as THz lens and THz generators. Although it seems no technical barrier to fabricating a moth-eye structure for THz waves, the practical uses of moth-eye structures are still limited by their weak mechanical stability. This dissertation focuses on the development of the moth-eye and related antireflective (AR) structures for the antireflection in the THz region and aiming at achieving a high-performance stable AR structure for the actual applications.

Chapter 1 briefly introduces the THz waves and their applications. The reflection loss which has been hindered the actual applications of THz devices in daily life is also introduced with conventional antireflection strategies. Moreover, the motivation and organization of this thesis are also described in chapter 1.

Chapter 2 describes the realization of moth-eye structure by using femtosecond laser processing. A processing system was built for the fabrication of moth-eye structures in the THz region. Thermal influence during laser processing on a high-resistivity Si substrate was studied, and neat moth-eye structures with different pitches and aspect ratios were successfully fabricated. The evaluation method based on a terahertz time-domain spectroscopy (THz-TDS) was established.

Chapter 3 introduces the applications of moth-eye structures to improve the output of a THz generator which is designed to meet the needs of developing a compact and high-power coherent THz wave source. This THz generator consists of a one-dimensional array of photoconductive antennas on a low-temperature-grown GaAs substrate. The challenge to the antireflection of Zinc oxide (ZnO) substrate is also performed because ZnO is also a potential material for the THz generator. Results of ZnO are not as good as desired, but the possible cause for the undesired results was discussed with the formation of defects on the laser-irradiated spots. Moreover, laser processing physics about this wide-bandgap material was also discussed with a multi-photon absorption model. Although without any post-processing, the laser-fabricated ZnO moth-eye structures did not achieve the desired AR performance, it was demonstrated that the AR performance can be improved by annealing such structures in the air.

Chapter 4 introduces further work for controlling the effective refractive index of moth-eye structures, which is aiming at the control of AR characteristics to improve their performance. Micro tapers with special profiles should have higher AR performance and mechanical stability than that of single-line laser-scanned moth-eye structures. An index was proposed to evaluate the total power reflectance in a broad THz band, and this index should be an important reference for the design of AR structures in the THz region.

Chapter 5 proposed a polymer-coated moth-eye structure with high AR performance and high mechanical stability. This hybrid ARS was made by filling a silicon-based moth-eye structure with silicon nano-particles dispersed polymer, subsequently coated by a polymer layer on the surface. This high-transmittance and cleanable flat AR surface should be useful for a lot of THz components in actual applications, such as the THz lens and generators.

Chapter 6 is the summary of this thesis. Future perspectives of moth-eye structures are also discussed in this chapter.

論文審査結果の要旨

This thesis consists of the following contents.
Chapter 1 describes the background of the THz waves and their applications. Then, the reflection loss which has been hindered the actual applications of THz devices is introduced with conventional AR strategies.
Chapter 2 describes the moth-eye structure by using femtosecond laser processing. Thermal influence during laser processing on a high-resistivity Si substrate was studied, and moth-eye structures with different pitches and aspect ratios were successfully fabricated. The evaluation method based on a terahertz time-domain spectroscopy was established.
Chapter 3 describes the applications of moth-eye structures to improve the output of a THz generator, consisting of a one-dimensional array of photoconductive antennas on a low-temperature-grown GaAs substrate. On the other hand, defects formed during laser irradiation of zinc oxide (ZnO) were also discussed to fabricate the moth-eye structure of ZnO substrates. Furthermore, it was demonstrated that the AR characteristics can be improved by annealing ZnO in the air.
Chapter 4 discussed controlling the effective refractive index of moth-eye structures, which is aiming at the control of AR characteristics to improve their performance. Micro tapers with special profiles should have higher AR performance and mechanical stability than that of single-line laser-scanned moth-eye structures. An index was proposed to evaluate the total power reflectance in a broad THz band.
Chapter 5 proposed a polymer-coated moth-eye structure with high AR performance and high mechanical stability. This hybrid AR stracture was made by filling a silicon-based moth-eye structure with silicon nano-particles dispersed polymer, subsequently coated by a polymer layer on the surface.
Chapter 6 summarized this thesis. Future perspectives of moth-eye structures are also discussed in this chapter.
As mentioned above, in this thesis, systemic research for the moth-eye structures in THz frequencies, mainly from 0.1 to 2.5 THz, was performed for pursuing a high antireflection (AR) performance and high mechanical stability to meet the actual applications. This work can not only promote the practical application of THz but also contribute to ultrafast laser-based precision processing technology. Thus, this is enough worth for PhD thesis.