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学位論文題目	Development of Intense and Ultrashort Terahertz Radiation Sources Using Semiconductor Surfaces under Magnetic Field
論文審査委員	主　査　教授　　　安藤　正海 助教授　　猿倉　信彦 助教授　　高木　紀明 教授　　　桑野　博（慶應義塾大学）

論文内容の要旨

Recent progress of ultrafast laser technology is now opening new prospects in various fields, including not only conventional physics but also biophysics and medical sciences. This is due to the fact that ultrafast lasers are capable of producing high-rate and stable optical pulse trains with sufficiently high-peak power, which is vital for ultrafast spectroscopy or material processing. As part of their many applications, ultrafast lasers are used as an excitation source for the generation of electromagnetic waves in the far-infrared region, which is now known as terahertz (THz) radiation. The generation and detection of THz-radiation has been widely studied, due to its potential importance in a wide range of applications, including sensing/imaging of biomaterials or identification of environmental contaminations. To facilitate such applied research, there is an urgent need to develop a compact light source capable of producing intense and ultrashort THz-radiation. To date, various THz-radiation sources including photoconductive switches, semiconductor surfaces, and the nonlinear optical process have been reported by utilizing ultrafast optical pulses. Among them, using semiconductor surface has attracted a great deal of attention, since it provides intense THz-radiation without chemical processes or microfabrication techniques for emitter preparation.

In this thesis, femtosecond-laser-irradiated InAs surface was used to generate intense and ultrashort THz-radiation, and the excitation-fluence and magnetic-field dependence of THz-radiation power was investigated. From these experiments, valuable results were obtained, which give us a clear insight in exploring the physical origin of THz-radiation from InAs. From the results of excitation-fluence dependence, it was found that there are two regions for the excitation-fluence dependence of THz-radiation power. At low excitation fluence, a quadratic-dependent enhancement of the THz-radiation power is observed with increasing excitation fluence. In contrast, at high excitation fluence, the enhancement factor is gradually reduced, and the radiation power becomes proportional to a logarithm function of the excitation fluence. These results can be explained by considering the photo-Dember field as the source of THz-radiation. It was concluded that the THz-radiation is mainly generated by the surge-current, which originates from the different diffusion velocities between photoexcited electrons and holes. For magnetic-field dependence, two completely different behavior were observed depending on the excitation fluence. These results are explained by taking into consideration the different mechanisms of magnetic-field induced enhancement of THz-radiation power. At low excitation fluence, the enhanced THz-radiation mainly originates from the carrier acceleration by the surface electric field. The Lorentz force changes the direction of carrier acceleration toward surface parallel, and the THz-radiation power is enhanced regardless of magnetic field direction. In contrast, at high excitation fluence, the surface electric field is almost screened out and the diffusion process becomes significant. By applying a magnetic field, the dipole is rotated to the direction in which the THz-radiation is efficiently or inefficiently extracted from the surface, and the radiation power is either enhanced or reduced depending on the magnetic-field direction. Moreover, the magnetic-field dependence of THz-radiation power was measured up to 27 T, which is the strongest magnetic field ever reported. This is a collaboration work with Tohoku University and some exciting phenomena were successfully observed. From these results, it is found that THz-radiation power saturates at approximately 3 T and also at 13 T, and that the THz-radiation power at 3 T is much higher than that at 13 T. This result leads to the conclusion that a 3 T magnetic field is optimum for the generation of intense THz-radiation from an InAs(100) surface. Additionally, a peak shift of THz-radiation spectrum toward lower frequency was observed with increasing magnetic field, and also a clear periodic structure in the THz-radiation spectrum at magnetic fields above 10 T. The physical origin of these phenomena is still under discussion, however, one possible explanation is given by the emergence of magneto-plasma effect. The experimental results prove that there is a big possibility of coming across really exciting results in the field of ultrafast laser technology in cooperation with high magnetic field.

To generate the maximum THz-radiation power at much smaller magnetic field, other promising material as a THz-radiation source was sought and focus was made on InSb(100) surface irradiated by a communication-wavelength fiber laser. It is found that at 1560-nm excitation, THz-radiation power from InSb is significantly enhanced by an external magnetic field, and the maximum radiation power is obtained at magnetic field of 1.2 T. There are two significant advantages of using InSb rather than InAs. One is the capability to use an Er:fiber laser as an efficient excitation source, since more compact and high-average power fiber lasers should be available in the near future with the rapid progress of these lasers for optical communication. The other is the low optimum magnetic-field that can be easily achieved with slight modification, or by scaling down the previously-designed 2-T magnetic circuit.

For the generation of broadband THz-radiation, focus was done on n-type InAs irradiated by ultrafast optical pulses, and the magnetic-field dependence of THz-radiation power was measured. The physical origin of the higher-frequency component is found to be the hybrid modes of coherent plasmons and longitudinal optical phonons. Additionally, it is also found that THz-radiation power from the hybrid modes can be enhanced by applying an external magnetic field. From the viewpoint of engineering, this is the significant advantage of using n-type InAs under magnetic field, since the broadband spectrum in this frequency region is strongly required for spectroscopic works, which cannot be achieved by other schemes.

In conclusion, the intense and ultrashort THz-radiation sources were successfully developed by using semiconductor surfaces under magnetic field. For InAs irradiated by 800-nm laser, the maximum radiation is achieved by applying a magnetic filed at 3 T, and some interesting phenomena induced by the emergence of magneto-plasma effect are clearly observed under the effect of high magnetic field. Additionally, using n-type InAs under magnetic field is found to be the practical method to generate broadband THz-radiation, and the origin of higher-frequency component is identified to the hybrid modes. For the application viewpoint, the compact THz-radiation source is required, and InSb irradiated by 1560-nm laser is found to be the promising light source, since more compact and high-average power fiber laser should be available in the near future with the rapid progress of these lasers for optical communication.

論文審査結果の要旨

1983年にAuston等により、超短光パルスレーザーを照射した光伝導スイッチから数百ギガヘルツの周波数を持つテラヘルツ電磁波が観測されて以来、様々な手法を用いたテラヘルツ電磁波発生の研究がなされている。X線は高い診断能力と医療被曝との両刃の剣の感があるが、テラヘルツ電磁波がエックス線の能力を持ち、かつ被爆のない線源になれば、医療分野、半導体プロセスや環境計測など様々な分野に大きく貢献するものと考えられる。テラヘルツ電磁波は光子エネルギーが非常に小さいことからセンシングやイメージングへの応用が考えられている。開発研究を行う上で重要な要素技術としてテラヘルツ電磁波の高強度化と広帯域化の二つがある。高橋君は、この点に着目し、耐用性・コストに優れ、扱いやすい半導体を用いて、その表面にフェムト秒レーザーを照射する簡便な発生法を採用し開発した。高橋啓司君の学位請求論文は8章からなる。第1章は、序論であり、本研究の背景と目的、第2章は、代表的テラヘルツ電磁波発生光源である、光伝導スイッチ、超格子構造、半導体表面、及び非線形光学効果を用いた手法について、その発生原理と特徴の詳述、第3章では、テラヘルツ電磁波の検出系として、ボロメーターの原理とパワー校正方法、およびスペクトル波形測定に利用したマイケルソン干渉計と時間分解干渉計の原理と特徴についての詳述、第4章では、InAs表面から放射されるテラヘルツ電磁波の励起強度依存性および磁場依存性を測定し、印加磁場がないときのテラヘルツ電磁波発生機構が拡散プロセスであることを明らかにするとともに、磁場印加によるテラヘルツ電磁波の増強機構が励起強度に依存して変化することを明らかにした。第5章では、InAs表面から放射されるテラヘルツ電磁波の磁場依存性を27テスラまで測定し、強磁場印加時にはマグネット・プラズマ効果によりサブテラヘルツ領域の電磁波が発生することやテラヘルツ領域においてInAsの屈折率が変化することを明らかにした。第6章では、InSbを小型ファイバーレーザー（1.56μm）で励起した場合には、1.2テスラの磁場印加時にテラヘルツ電磁波強度が最大となり、0テスラの場合と比較して100倍の増強が可能であることを明らかにした。第7章では、n型InAsを用いたテラヘルツ電磁波発生光源を開発し、コヒーレント・プラズモンとLOフォノンの結合で形成されるハイブリッドモードを用いることによりテラヘルツ電磁波の広帯域化に成功した。第8章では、本論文で得られた結論と今後の課題を示した。要約すると本研究では、フェムト秒レーザーを照射した磁場中の半導体表面から放射されるテラヘルツ電磁波の放射機構を明らかにし、高強度化と広帯域化に必要な指針を示すことができた。これらの成果は工業上寄与するところが多いと考えられる。なお、研究遂行能力は十分にあると認められる。これらによって、高橋君は博士（工学）の学位を受ける資格があるものと認める。

なお、口述試験において審査委員から基礎及び専門学力確認のため、(1)光コヒーレンスの概念、(2)光干渉計の原理、パラメトリック散乱等の試験問題が出題されたが、いずれの問題に対しても合格点に達する回答が得られた。学位論文以前に十数編の英語論文を執筆していること、国際集会において英語での発表を数回行っていることから十分な英語能力を有していると判断した。また、公開発表会においても質疑応答に対しても的確な応答を行い、申請者は博士(工学)に相応しいと判断した。