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学　位　論　文　題　目	Development of Compact and Room Temperature Operating THz Light Sources （小型室温動作テラヘルツ光源の開発）
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論 文 内 容 要 旨

1. Introduction.

The lack of a high-power, low-cost, portable room temperature operation THz source is the most significant limitation of modern THz science. An attempt has been made to develop the room temperature operating compact THz sources. In this project, Electronic and photonic approach has been adapted to develop the compact THz systems. In the electronic approach a new, cavity less TUNNETT oscillator system is proposed for sub-THz wave generation. In the photonic approach, room temperature THz emission from bulk Ge and Si crystals were observed for the first time by photoluminescence emission mechanism. THz emission characteristics such as, resistivity and thickness dependence of THz emission from Ge crystals were studied. An attempt has been made to develop nondestructive imaging system from the new type Ge THz emitter. A proposal has been made to use the Ge- THz emitter in information and communication technology.

2. Patch antenna coupled GaAs TUNNETT oscillator.

Waveguide resonators in its simplest forms are metallic enclosures or cavities. Electric and magnetic energy is stored in this volume thus establishing a resonance condition. When the oscillation frequency is going into the THz regime, the conventional rectangular metal cavity will be difficult to be formed due to its machinery accuracy.

The other drawbacks in using the metal cavity as resonator are, (i) high fabrication cost (ii) highly direction dependent, this is the main limitation in applying cavity resonators in communication (iv) Integration with microwave integrated circuits (MICs) is difficult. To overcome these problems, a new type of oscillator system (patch antenna coupled with TUNNETT oscillator) has been developed. Conventional patch antenna consists of a pair of parallel conducting layers separated by a dielectric substrate. The patch is generally made of conducting material and can be designed for any possible shape. Upper conducting layer is the source of radiation where electromagnetic energy fringes off the edges of the patch and waves will penetrate into the insulating substrate.

The lower conducting layer acts as a perfect reflecting ground plane, where the wave energy bounces back through the substrate and then the electromagnetic wave is emitted into the free-space. The antenna size mostly depends on the frequency band of operation. The other factors to be considered in deciding the fringing and the wave propagation in the patches are dielectric constant of the substrate and thickness of the insulating substrate . The excitation of the patch is accomplished via a microstrip feed line. This feed technique will supply the patch with electrical signal to be converted into an electromagnetic wave.

Patch antenna dimensions such as the slot length, slot width, patch sizes and dielectric substrate thickness were optimized using Mstrip40 program for 200 and 300 GHz emission. The pattern of the patch antenna was fabricated by the conventional photolithography method A 500 μm × 500 μm × 300 μm thick diamond heat sink is metalized with Au, and then the diamond heat sink is die-bonded to an Au coated Cu stem. AuGe foil is used as bonder.

A 100×100 μm TUNNETT diode was press bonded on to the Au plated diamond heat sink. The fabricated patch antenna with dimensions of 390 μm × 440 μm with the bias pad of 500 μm × 500 μm is bonded to the Cu stem. The patch antenna is connected with the TUNNETT diode on the diamond heat sink. The TUNNETT diode cathode is connected with a 120 μm width and 12 μm thick Au ribbon, to the patch antenna.

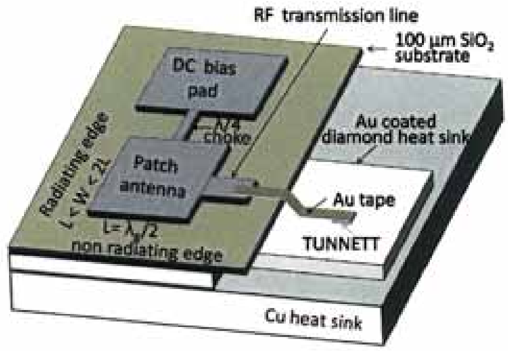

Fig. 1 Schematic diagram of patch antenna coupled TUNNETT oscillator

After successful fabrication of patch antenna coupled TUNNETT oscillator, oscillation testing were carried out. A frequency and power measurement system was set up for this purpose. Frequency measurement was carried out using the Fabry-Perot interferometer with the Si bolometer. Tektroniox 2784 spectrum analyzer with SBD harmonic mixer was used for evaluating the RF power. Obtained results are shown in figure 2.

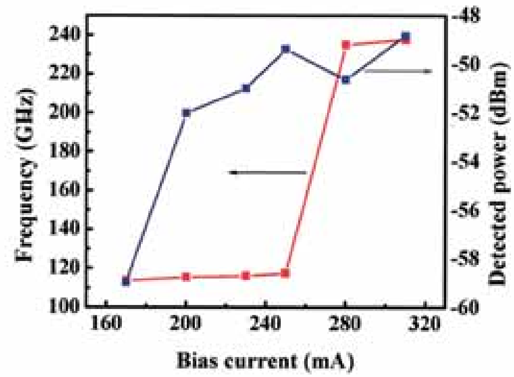

Figure 2. Oscillation frequency and detected radio frequency (RF) power versus the bias current of 300 GHz design patch antenna. The bias current varied from 150 to 300 mA.

3. **Room temperature spontaneous THz emission from Ge and Si**

Room temperature THz emission is observed from Ge and Si crystals. It is a new observation ever reported by photoluminescence emission mechanism at room temperature. The THz emission mechanism can be considered as follows. Electrons, which are optically excited from the valence band into the conduction band, will recombine with holes in the valence band via shallow donor levels giving rise to THz emission. The energy level difference between the conduction band and the donor energy level (E_C-E_D) corresponds to the THz emission energy. In the case of Ge, the ionization energy is around 10 meV. Electron transition between the conduction band and shallow donor level is a dynamic process. So, the THz emission continue to occur even at room temperature because of the very short life time, even though the amount of thermally re-excited electrons from the shallow donor level to the conduction band may be considerable, when the Fermi level position is well below the conduction band minimum.

4 Results and discussion

Typical THz emission spectrum observed at room temperature from *p*-Ge (ρ ~17 Ωcm) and *n*-Ge (20 Ω cm) is shown in Fig. 3. The observed THz emission spectrum includes grating efficiency and filter characteristics. Intentionally doped Ge crystals have shallow energy levels at around 10meV. In this case, Ga is the dopant in *p* type Ge and Sb is the dopant in *n*- type Ge. When the excited electrons recombine to the holes in the valence band, it makes transition through shallow energy level. The shallow energy level is located at around 10meV from the conduction and valence band which corresponds to 2.4THz.

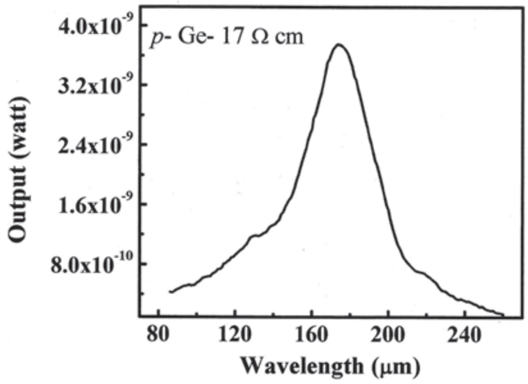

Figure 3. Typical THz emission spectrum of *p*-Ge at room temperature

The excitation sources were blue LED and NIR-LED. To investigate the heating effects of the LED, transit time comparison was carried out to confirm the true THz emission. Elemental and compound semiconductors were tested for room THz emission and it was observed that Si and Ge only emitting THz at room temperature by photoluminescence mechanism. Estimation of wavelength was carried out using the filter characteristics of silicon bolometer.

THz emission characteristics such as, resistivity and thickness dependence of THz emission from Ge crystals were studied. Si and Ge THz emission spectrum comparison were carried out; Wavelength difference in Si and Ge THz emission spectra shows the shallow energy level difference.

Figure 4 shows the resistivity dependence of THz emission of *p*-Ge. It has been observed that the output power increased with increasing resistivity. The carrier concentration and the resistivity is inversely proportional, thus the reduced free carrier absorption leads to higher THz emission intensity. The intensity of the THz emission is higher (3.94 x10^{-9} W) for higher resistivity sample (ρ~17Ωcm). The lower intensity was observed for ρ~0.28Ωcm resistivity with the output power of 3.18 x10^{-11}W. The intensity is two orders of magnitude higher than that observed by the lowest resistivity sample.

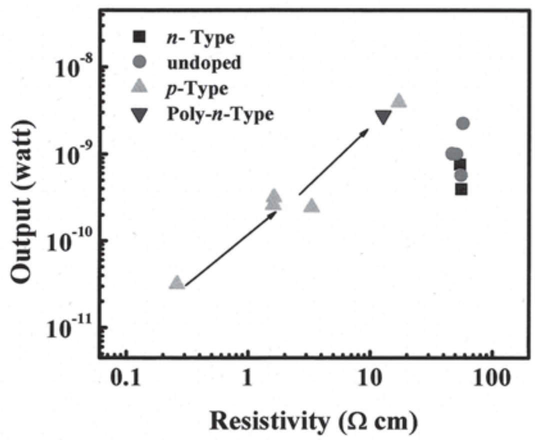

Figure 4 THz emission output power as a function of resistivity from *p*-Ge with almost the same wafer thickness of about 350μm.Excitation source was LED with the optical output power of 45 mW.

Improvement of THz emission output power from Ge by Deep level introduction by lattice defects.

For practical applications we need high power THz emission from Ge. It is considered that, emitted THz wave were again absorbed for excitation of free electron in Ge. In order to understand the detailed THz emission mechanism and to improve the output power of room temperature operating Ge THz emitter, the introduction of deep levels by the lattice defect is efficient in view of the control of Fermi level position of Ge for the enhancement of PL THz emission.

It has been found that if *n* type Ge is heated above 500°C for few minutes, Ge crystals are converted to or towards *p*-Ge . Thermally produced *p*- type carriers may be the result of acceptor levels introduced by the lattice defect produced by physical displacement of the Ge atoms from the normal site . thermally produced acceptors are produced at the surface of the crystal as vacancies and diffuse into the bulk of the crystal. Vacancies can act as an acceptor; it is assumed that each vacant site may be able to accept a maximum number of one electron. Based on the available theories, an attempt was made to improve the THz emission from Ge at room temperature. Here in these experiments, *n* type Ge crystals were annealed at different annealing temperatures (853 K to 1000K) to introduce the lattice defects, the obtained results are shown in the Fig 5. The annealed sample shows maximum PL-THz emission intensity than the not annealed samples, which confirms the THz emission is affected by the free carrier available in the Ge at room temperature.

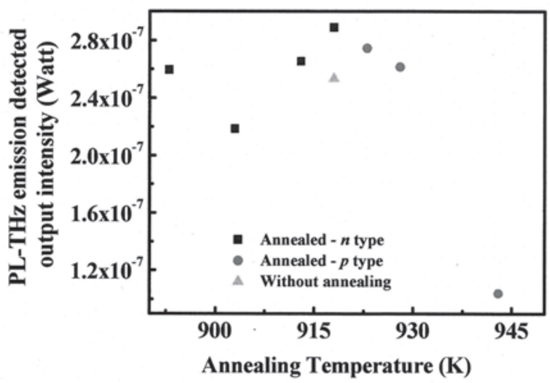

Figure 5.13 THz emission as a function of annealing temperature from *n*- Ge. Carrier type inversion is achieved from *n*-to *p* Ge. THz emission is higher at the carrier conversion temperature.

論文審査結果の要旨

電波と光の中間周波数帯に位置するテラヘルツ(THz, Terahertz, 1 THz=10^{12} Hz)波は，永年、未開拓な周波数帯域であったが、近年ようやくその基礎科学・応用分野の重要性が認識されはじめた．THz 帯域には固体物質中のフォノン，生体分子の固有振動，分子間相互作用に関連したエネルギー準位が数多く存在すると考えられており、新規医薬品開発やガン検出・治療，医療イメージングや人体に安全な非破壊検査そして超高密度光空間通信など、広範な応用が期待されている．そのため、近年、高品質 GaP 半導体結晶の非線形光学現象を用いた差周波混合によるパルス及び CW 波 THz 発生技術やフェムト秒レーザーによる時間領域 THz 分光あるいは量子カスケートレーザー等が開発されている.しかし、これらの光源は大型装置である点や低温動作が必要である等、工業的応用の面で克服すべき大きな課題があった.
本論文は、小型で室温動作が可能である連続波（CW）テラヘルツ電磁波発生を目指し、THz 帯小型アンテナデバイスと結合した半導体電子デバイスの高周波化と、半導体結晶中の光学遷移を利用した新たな THz 波発生機構により実現した成果をまとめたものであり、全７章よりなる.

第１章は序論であり、本研究の背景と目的、そしてその目的を達成するための半導体電子デバイスと半導体光デバイス両面からのアプローチについて述べている.

第２章では、THz 半導体電子デバイス（タンネットダイオード）のトンネル注入走行時間効果に基づく THz 電磁波の発生原理とデバイスデザインについて記述している．更に、それを実現するための半導体超薄膜デバイスエピタキシー技術とデバイスプロセスについて述べている.

第三章では、タンネット電子デバイスを小型平面アンテナデバイスに結合し、室温 CW の THz 発生を実現した結果を述べるとともに、平面アンテナ構造のインピーダンス整合設計ルールについても述べている.

第四章では、半導体中の浅い準位間光学遷移に基づく新たな THz 波発生について、Ge と Si からの基本的発生特性と発生メカニズムについて述べている．また、発生 THz 光の周波数特性を分光するための、独自の THz 帯グレーティング分光装置の構築についても述べている.

第五章は、四章で述べた半導体中の光学遷移による THz 波発生を高効率化するため、熱処理や遷移金属元素添加により欠陥準位を導入してフェルミ準位を制御し、導電型反転及び高抵抗化を達成して、高効率発生を実現した結果を述べている.

第６章はこれら小型室温動作 THz 光源の応用について述べている．その中で、小型 THz 光源を用いた非破壊検査応用のイメージング装置構成とその実例、更に THz 通信応用として光源の基本的な変調実験結果を述べている.

第七章は本論文の総括である.
以上要するに、半導体電子デバイスと半導体光デバイスの両側面から小型室温動作 THz 光源の実現を目指し、電子デバイスとしては小型平面アンテナに結合したトンネル注入走行時間効果素子光源により 0.3THz に迫る超高周波発生を実現し、光デバイスとしては「指先サイズ」をも可能とする半導体中の浅い準位間光学遷移に基づく新たな THz 波発生とその高効率化を実現したものであり、材料物性学の発展に寄与するところが少なくない.

よって，本論文は博士(工学)の学位論文として合格と認める.