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研究課題名（英文） Terahertz quantum cascade lasers based on (GaN)m/(AlN)n monolayer superlattices in order to exploit their potential for high temperature operation

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研究成果の概要（和文）：本研究は、未だ実現していない5-12THz帯のテラヘルツ量子カスケードレーザ(THz-QCL)を新規開拓することを目的としている。現行で用いられているGaAs系材料ではLOフォノン散乱による強い光吸収のため発振周波数の拡張は難しい。一方、本研究で"新しい材料"として着目したAlGaN系 III族窒化物半導体はLOフォノンエネルギーがGaAs系材料に比べ3倍程度大きいため、これまで未開拓であった5-12THz帯でのレーザ発振が可能 である。本研究では、窒化物半導体膜の高品質化、新しい量子構造の導入を行うことで、未踏周波数領域(5-12THz)を中心としたTHz-QCLの実現を目指す。

研究成果の学術的意義や社会的意義
テラヘルツ量子カスケードレーザ(THz-QCL)は小型、高出力、狭線幅、安価、連続動作可ななテラヘルツレーザ光源として今後の実用化が期待されている。既にテラヘルツパラメトリック発振器などを用いて実用化しているテラヘルツ分析装置、各種透視・非破壊検査用の光源の置き換え、また、携帯用の検査用レーザ光源としての応用が期待されている。テラヘルツ光源の応用範囲は、郵便物や税関検査などのセキュリティ検査、食品などの異物混入検査、ICチップ検査などの電子産業への応用、火傷診断、癌細胞の識別、虫歯の検査などの医療応用、農作物検査、構造物内部の検査など、非常に広範囲にわたる。

研究成果の概要（英文）： The GaN THz QCL waveguides are carefully investigated. The possible methods have been developed to fabricate low loss and high confinement waveguide for both single-metal-surface-plasmon and double-metal designs. Epitaxial growth technology for GaN/AlGaN THz QCL structures have been developed by using both MBE and MOCVD methods. High quality QCL structures have been achieved.
A Non-Equilibrium Green’s Function (NEGF) method has been used to analyse the carrier transport and gain properties of GaN/AlGaN THz QCL structures. The gain is calculated in a self-consistent way accounting for the correlation effects in the broadening of different levels. The simulation results demonstrate that the gain spectra can be narrow enough and the peak gain can be high enough for lasing at 7 THz at 280 K for a preliminary design.

研究分野： III nitride semiconductor physics and devices

キーワード： Quantum cascade laser　MBE　GaN

１．研究開始当初の背景

Terahertz (THz) quantum cascade lasers (QCLs) are semiconductor-based compact coherent THz sources, which employ inter-subband transitions and carrier recycling in periodically stacked superlattices. The operating-frequency of traditional GaAs based THz QCLs covers from 1.2 to 5.4 THz. However, the progress to achieve high operation temperatures has been slowed down since 2007, in which year it reached 170 K. So far the maximum operation temperature is about 190 K. This limitation is intrinsic for GaAs, due to the small LO phonon energy, 36 meV, which enables thermally activated quick nonradiative phonon emission at elevated temperatures, and severe thermal back filling. Consequently, it results in not enough population inversion and suppressing THz radiation. Furthermore, excitation of these vibrational modes provides a large absorption mechanism for light at the similar frequencies (reststrahlen absorption). The GaAs based THz QCLs cannot work at above 5 THz.

III-nitride semiconductors are a new material system for fabricating tera hertz (THz) quantum cascade lasers (QCLs), the most promising electrically pumped and compact THz radiation sources. III-nitrides offer potentials to achieve high temperature (>200 K) operating THz QCLs, which is the intrinsic upper limit for conventional GaAs/AlGaAs THz QCLs. However, it is still an extremely difficult task to grow GaN/AlGaN THz QCLs by using current growth technologies.

２．研究の目的

III-nitride growth technologies have not yet reached the same maturity level as GaAs or InP, mainly due to the large lattice/thermal mismatch to foreign substrates and even between GaN/InGaN/AlGaN themselves. The extremely large built-in electrostatic fields, due to both spontaneous and piezoelectric polarization charges at the hetero-interfaces, make the design and simulation much more complicated. The polarization field is on the order of 0.1-1 MV/cm, and consequently, the conduction band profile is saw-tooth like shape, which leads to complicated band-engineering for design of the QCL active region. Moreover, the strong electron-LO-phonon interaction in GaN, with a Fr€ohlich constant 16 times stronger than in GaAs, could be expected to be a limitation in terms of lifetimes and level broadening. A careful study of the broadening mechanism is therefore needed for analysis and design of GaN THz QCL.

Besides the difficulties in designing the QCL active region and growth technologies, another important aspect to achieve a working GaN QCL is the waveguide design, the investigation of which has been lacking so far. A waveguide with low loss and high confinement factor is beneficial for reducing the threshold gain for lasing.

３．研究の方法

In this work, we use a Non-Equilibrium Green ’ s Function (NEGF) method to analyse the carrier transport and gain properties of GaN/AlGaN THz QCL structures. All scattering processes are calculated on a microscopic basis. A considerable advantage of the NEGF formalism is the built-in description of the time-energy uncertainty principle linking the calculation of the scattering processes and the level broadening. In addition, the gain is calculated in a self-consistent way accounting for the correlation effects in the broadening of different levels. Indeed, the gain linewidth can be smaller than the one of individual levels.

This research also investigated the possible waveguides for GaN THz-QCLs. Design of double metal waveguides (DMW) can give the highest optical field confinement and lowest cavity loss. We then developed technologies to use easy removal substrate, such as Si, which can be wet etched. Top metal and bottom metal cladding layers can be fabricated in the usual way. The metal layers are essential to confine the optical field. The single metal plus bottom n++ surface plasmon layer is another way to form relative good confinement. For this purpose, the various substrates for GaN/AlGaN hetero-epitaxy much be check carefully.

４．研究成果

Carrier transport in GaN terahertz (THz) quantum cascade laser (QCL) structures is theoretically investigated using a non-equilibrium Green ’ s function method. Although scattering due to polar optical phonons in GaN is greatly enhanced with respect to GaAs/AlGaAs THz QCLs, the phonon induced broadening of the laser levels is found to remain much smaller than other sources of broadening arising from impurity and electron-electron scattering. The gain is calculated self-consistently accounting for the correlation effects in level broadening. Three-well based design with resonant phonon scheme shows a peak gain of 88/cm at 10K, and 34/cm at 280 K, which remains above the calculated loss of a double metal waveguide. The results suggest that lasing at 6.6THz, which is beyond the traditional GaAs THz QCLs, is possible up to 280 K.

We have analyzed the waveguide loss originating from various doping layers in double metal waveguides for potential GaN-based terahertz quantum cascade lasers (THz QCLs) by theoretical calculations. The optical field can be very well confined in the active QCL region. Average electron densities in the QCL active region and n+ contact layers should be controlled carefully. The loss in the low-frequency range (≤3 THz) can be minimized by decreasing the electron density in the QCL layer. In the middle- and high-THz-frequency ranges (3 < f < 15 THz), the absorption by the heavily doped n+ contact layer dominates the waveguide loss. Consequently, the bulk plasma frequency, which is determined by electron density and shows a strong absorption peak, must be tuned to deviate from the target QCL frequency. The waveguide loss plus the cavity mirror loss can be controlled to be as low as 24/cm.

With the support of this research, we have designed practical GaN THz QCL active region with high peak gain and lasing is possible at room temperature, and the waveguide design for various substrates and for both DMW and single metal waveguides have also been carefully investigated.

５．主な発表論文等

〔雑誌論文〕（計　5　件）

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〔図書〕（計　　件）

〔産業財産権〕
○出願状況（計　1　件）

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発明者：Li Wang, T.T. Lin, Ke Wang, H. Hirayama
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〔その他〕
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