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Fabrication and characterization of a quasi-phase-matched GaP optical device for terahertz-wave generation

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ABSTRACT

A method of fabricating a quasi-phase-matched optical device with GaP for terahertz (THz)-wave generation is described, and its generation at 1 and 2.6 THz is demonstrated by employing difference-frequency generation pumped at 1.55 μm. The enhancement of the output THz-wave power due to the quasi-phase-matching effect is confirmed, and an order of magnitude larger output efficiency than that of an ordinary quasi-phase-matched device fabricated with $LiNbO_3$ is obtained. Some important factors that affect the output characteristics of the GaP device are also discussed.

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1. Introduction

Recent great advancement in electrical, optoelectronic, and laser devices has made it possible to generate electromagnetic waves from the sub-THz to the THz region and promotes their applications to various scientific and industrial fields, e.g., imaging for biomedical diagnosis, spectroscopy for the chemical identification of large complex molecules, and sensing for security [1–4]. Electromagnetic-wave sources based on electrical and optoelectronic devices, such as frequency multipliers [5] and photomixing sources with low-temperature-grown GaAs [4] or uni-traveling-carrier photodiodes [6], can be used for those applications because they are stably operative at room temperature. But, those devices have an upper limit to the output frequency at less than 1 THz because of their limited carrier response time and RC time constant [4–6]. On the other hand, a laser-based source, e.g., a quantum cascade laser [7] or a *p*-Ge laser [8,9], is operative in the THz region, and yet this type of source does not work well at room temperature because, as the output frequency approaches the THz region, the energy gap used for lasing becomes comparable to the thermal energy at room temperature.

In order to avoid those drawbacks, a different method can be adopted, which is to use nonlinear optical effects. The aim of this paper is thus to present a nonlinear optical source for efficient THz-wave generation at room temperature and to clarify its basic characteristics. In the next section, we describe the nonlinear effect and material that we selected in this paper. In Section 3, we explain the method to enhance the output THz-wave power by employing quasi-phase-matched structures. In Section 4, we introduce how to fabricate our quasi-phase-matched device. In Section 5, we show experimental results for THz-wave generation with our device. In Section 6, we discuss factors that significantly influence the output characteristics of our device. Finally, we provide a summary in Section 7.

2. Selection of nonlinear optical effect and material

There are numerous reports on THz-wave generation by using nonlinear optical effects related to $\chi^{(2)}$-nonlinearity, such as optical parametric oscillation [10,11], difference frequency generation (DFG) [12–17], and optical rectification (OR) [18–22]. These nonlinear effects are attracting much attention because of their high-power capability and room-temperature operation, which are important for device application.

Among them, particular attention should be paid to DFG or OR using zinc-blende semiconductors (e.g., GaAs, GaP, and ZnTe). This

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is because it has an advantage that unlike optical parametric oscillation, it requires no threshold pump power [23] and that low-power light sources can be used for pumping. Moreover, the second-order susceptibility $\chi^{(2)}$ of those semiconductors at near-infrared wavelengths is a few times larger than that of typical $\chi^{(2)}$ materials such as lithium niobate [24], and their absorption coefficient in the THz region is about ten times smaller than that of lithium niobate ($\sim$20 cm^{-1}) [15]. Thus, high-power output can be expected.

Reports have recently been published on a THz-wave source with 2-cm-long, bulk GaP employing DFG with a pump wavelength of $\sim$1 μm [13,14]. Here, this pump wavelength was chosen so that phase matching utilizing phonon–polariton dispersion could work to achieve high-output efficiency. Also, a THz-wave source with periodically $\chi^{(2)}$-inverted GaAs employing OR pumped at 2–4 μm has been reported recently [19,20], where the mid-infrared wavelength was used to avoid the large optical loss caused by two-photon absorption.

If we consider a small THz-wave device to be built in the near future, the use of a pump wavelength of 1.55 μm will be meaningful because small high-power semiconductor light sources being developed at this wavelength for optical-communication systems can be used as pump-beam sources. Furthermore, if we select GaP, not GaAs, for such a nonlinear THz-wave device, the optical loss at 1.55 μm will not be noticeable. Indeed, the loss of GaP containing two-photon absorption is much smaller than that of GaAs because of large bandgap energy: $E_g^{\mathrm{GaP}} = 2.2$ eV $> E_g^{\mathrm{GaAs}} = 1.43$ eV (cf., the photon energy of 1.55 μm pump beams: 0.8 eV).

In addition, if we adopt DFG, not OR, it is operative even in quasi-CW operation. However, when we employ DFG for THz-wave generation with GaP pumped at 1.55 μm, its coherence length ℓ_c is relatively small, which is on sub-millimeter order, and the output power is also small because it is proportional to ℓ_c^2, as obtained from a simple model calculation [25,26]. Fortunately, we can avoid this drawback by using the method of quasi-phase matching (QPM) with a periodic $\chi^{(2)}$ structure. If this structure has a length of $N\,\ell_c$, then the output power will be enhanced proportionally to N^2. Thus, in this paper, we will make a THz-wave source with a periodic $\chi^{(2)}$ structure of GaP employing DFG pumped at 1.55 μm.

Note that QPM with periodic $\chi^{(2)}$ structures for power enhancement is a fairly general and useful method, which is feasible even in non-semiconductor materials such as glasses, where the method of optical poling can be used to form periodic $\chi^{(2)}$ structures [27,28].

3. How to realize optical devices with periodic $\chi^{(2)}$ structures

In order to fabricate periodic $\chi^{(2)}$ structures with semiconductor materials, a number of methods have been proposed so far. For instance, spatially-modulated implantation of high-energy ions into III–V semiconductors can be used for them because the implanted parts are disordered and their nonlinearity is much decreased [29,30]. But, this method does not allow us to utilize $\chi^{(2)}$-nonlinearity in the most effective way, since its structure has a period of $\chi^{(2)}, 0, \chi^{(2)}, 0, \chi^{(2)}, 0, \ldots$, not $\chi^{(2)}, -\chi^{(2)}, \chi^{(2)}, -\chi^{(2)}, \chi^{(2)}, -\chi^{(2)}, \ldots$

If possible, the latter configuration should be realized. A simple way to realize it is to rotate the crystal orientation of $\chi^{(2)}$ by 180 degrees partially so that $\chi^{(2)}$ and $-\chi^{(2)}$ domains can align periodically. This has recently been achieved experimentally, and the structure with it is called a periodic orientation-patterned structure.

To fabricate this structure, one first bonds a semiconductor wafer with $\chi^{(2)}$ whose $\chi^{(2)}$-direction is perpendicular to the wafer surface and another wafer with $-\chi^{(2)}$ by the direct-wafer-bonding technique [31]. Next, one of the wafers is etched so that semiconductor islands with $\chi^{(2)}$ (or $-\chi^{(2)}$) are left periodically on the wafer with $-\chi^{(2)}$ (or $\chi^{(2)}$), respectively. Finally, regrowing the same material on it, one obtains a periodic orientation-patterned structure. Employing this method, Yoo et al. fabricated a $\chi^{(2)}$-inverted structure of AlGaAs on a GaAs substrate [32]. In addition, Koh et al. used Ge islands in place of the etched semiconductor $\chi^{(2)}$ islands and fabricated a $\chi^{(2)}$-inverted structure of GaAs [33]. But, the shortcoming of those methods is that the interfaces between $\chi^{(2)}$ and $-\chi^{(2)}$ domains formed in the regrowing process are not well made, thereby causing large optical scattering loss.

Another way to make a $\chi^{(2)}$-inverted structure is to attach a semiconductor chip with $\chi^{(2)}$ whose $\chi^{(2)}$-direction is parallel to the chip surface to another chip with $-\chi^{(2)}$ and to bond many pairs of them so that they can form into the periodic structure of $\chi^{(2)}$ and $-\chi^{(2)}$. In this method, the thickness of the chips has a low limit, typically on the order of sub-millimeters, because manipulating very thin fragile wafers is not easy in mechanical handling. Gordon et al. managed to make a $\chi^{(2)}$-inverted structure of GaAs by this method and succeeded in second-harmonic generation of a 10.6 μm CO_2 laser beam passing through it [34].

Fortunately, the thickness that we need in THz-wave generation with an output wavelength of a few hundred microns by DFG is on the order of sub-millimeters, so that we can still handle the chips and fabricate a $\chi^{(2)}$-inverted structure. As mentioned, we will make this structure with GaP, not GaAs, and in addition to its good optical characteristics, it has a good property in fabrication: GaP is almost transparent for visible light, so that when we bond GaP chips, the contact condition between them can readily be evaluated by our eyes. But, GaAs is not transparent for visible light, so that the contact condition is not checked until optical loss measurement is performed with infrared light sources.

4. Fabrication of our nonlinear THz-wave device

The coherence length ℓ_c, or the wafer thickness W, for THz-wave generation by DFG with first-order QPM is calculated from the relation $\ell_c = c/|2(n_{\mathrm{THz}} f_{\mathrm{THz}} - n_1 f_1 + n_2 f_2)|$, where c is the velocity of light, f_1 and f_2 are the input pump-beam frequencies, $f_{\mathrm{THz}}(=f_1 - f_2)$ is the output THz-wave frequency, and $n_i = n(f_i)$ is the refractive index depending on f_i for $i = 1, 2$, or THz with the parameters of Ref. [35]. For instance, Fig. 1a shows ℓ_c for 1-THz output as a function of pump wavelength λ_1 ($=c/f_1$). For 1.55 μm pumping, ℓ_c becomes 0.75 mm. Thus, we can see that wafers with this thickness are still manipulated by hand.

As for the crystal orientation of the GaP wafer, it is selected so that the output power will be maximal. Since GaP belongs to the $\bar{4}3m$ point group symmetry and has non-vanishing elements of $\chi^{(2)}_{14}, \chi^{(2)}_{25}$, and $\chi^{(2)}_{36}\left(\chi^{(2)}_{14} = \chi^{(2)}_{25} = \chi^{(2)}_{36}\right)$, when we use commercially available (1 1 0) wafers, if we select the $\langle 1\,1\,1\rangle$ direction for periodic inversion, then the maximum output power will be obtained [36]. Calculation results on this are illustrated in Fig. 1b. Here, pump beams propagating in the $\langle 1\,1\,0\rangle$ direction with a polarization direction having an angle ϕ to $\langle 0\,0\,1\rangle$ produce output waves with a total power of $P_{\mathrm{total}} = P_{\mathrm{para}} + P_{\mathrm{perp}} \propto (1/4)\sin^2\phi[4 - 3\sin^2\phi]$, indicated by a dashed line. Here, $P_{\mathrm{para}} \propto (9/4)\cos^2\phi\sin^4\phi$ is a power whose polarization is parallel to that of the pump beams (Fig. 1b, thick line) and $P_{\mathrm{perp}} \propto \sin^2\phi[\cos^2\phi - (1/2)\sin^2\phi]^2$ is a power whose polarization is perpendicular to that of the pump beams (Fig. 1b, thin line) [37].

In Fig. 1b, it is clear that a polarization angle of $\phi = 54.7^\circ$ or 125.3° (i.e., a polarization parallel to $\langle 1\,1\,1\rangle$) provides the maximum power without including the perpendicular component P_{perp}. Thus, if we let pump beams propagate in the $\langle 1\,1\,0\rangle$ direction with the $\langle 1\,1\,1\rangle$-polarization direction, we can easily check if the generated signals are THz waves or randomly polarized thermal radia-

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