Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Solid-State Electronics 51 (2007) 1319–1327
SOLID-STATE ELECTRONICS
www.elsevier.com/locate/sse

Emission of terahertz radiation from InGaP/InGaAs/GaAs grating-bicoupled plasmon-resonant emitter

Taiichi Otsuji [a,*], Yahya Moubarak Meziani [a], Mitsuhiro Hanabe [a], Takuya Nishimura [a], Eiichi Sano [b]

[a] *Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan*
[b] *Research Center for Integrated Quantum Electronics, Hokkaido University, Sapporo 060-8628, Japan*

Received 30 March 2007; received in revised form 2 July 2007; accepted 7 July 2007
Available online 22 August 2007

The review of this paper was arranged by Stephen Goodnick, Anatoli Korkin, Toshio Naito and Nasser Peyghambarian

Abstract

We have designed and fabricated an optically-pumped plasmon-resonant terahertz emitter incorporating doubly interdigitated grating gates and a vertical cavity into an InGaP/InGaAs/GaAs high-electron mobility transistor structure. The two-dimensional (2D) plasmon layer is formed with a quantum well in the InGaAs channel layer. When the dual grating gates are biased at different levels, the sheet carrier density is periodically modulated, making periodic 2D plasmon cavities along with the grating. When the device is photoexcited by laser irradiation, photoelectrons, injected to the cavities, excite the plasmons, leading to the emission of terahertz radiation. The fabricated device is subjected to 1550-nm, 1-mW (a) a single CW-laser, (b) 4-THz photomixed dual CW-laser, and (c) a 70-fs pulsed-laser illumination at room temperature. In case of (a), terahertz emission is detected by a Si bolometer under certain bias conditions, which is inferred to be due to the self oscillation stimulated by the plasmon instability. In case of (b), a resonant peak of injection-locked 4-THz oscillation is clearly observed on the device photoresponse. In case of (c), an impulsive radiation followed by relaxation oscillation is observed by electrooptic sampling, whose Fourier spectrum exhibited resonant peaks of plasmons' harmonic modes up to 4 THz. Estimated radiation power exceeds 0.1 μW, resulting in excellent conversion efficiency of the order of 10^{-4}.

PACS: 73.21.−b; 73.22.−f; 73.50.Mx; 73.61.Ey; 73.63.Hs; 78.45.+h

Keywords: Plasmon; Terahertz; Emitter; Photomixing; Grating; HEMT

1. Introduction

Optical heterodyne conversion, or photomixing, in semiconductors is a popular technique to generate continuous-wave (CW) coherent terahertz radiation at room temperature. Extensive studies on terahertz photomixers utilizing low-temperature-grown GaAs (LT-GaAs) photoconductors (PC's) [1–4] and pin photodiodes (PD's) [5] as well as uni-traveling-carrier photodiodes (UTC-PD's) [6] have been made over the last decade. So far, excellent performance of over 5-THz generation by using LT-GaAs' PC's [1] and over 10-μW emission power at 1.04 THz by using UTC PD's [6] have been demonstrated. At the same time, those PC's and PD's can serve as terahertz pulse emitters when they are excited by femtosecond laser pulses. Their quantum efficiencies, however, are substantially limited by their two-terminal device structures although new challenging works including traveling-wave structures [2,4] and/or ballistic transport structures [7] have been emerging. New principle of operation, therefore, should be appreciated to breakthrough the limit.

---

[*] Corresponding author. Tel./fax: +81 22 217 6104.
E-mail address: otsuji@riec.tohoku.ac.jp (T. Otsuji).

0038-1101/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.sse.2007.07.017

Two-dimensional (2D) plasmons in submicron transistors have attracted much attention due to their nature of promoting emission of electromagnetic radiation in the terahertz range, which is expected to realize frequency-tunable emitters/photomixers as well as frequency multipliers [8–20]. Those previous works except [15] and [16] utilized DC-current-driven plasmon instability for emission of terahertz or sub-terahertz radiation, showing broad emission spectra even at cryogenic temperature. This is because electrical DC-current flow may excite various structure-dependent plasmon modes including *gated* and *ungated* regions [20,21]. Sekine et al. observed clear emission peaks spectrum of terahertz radiation stimulated by impulsive Ti:sapphier laser excitation at cryogenic temperature, suggesting possibility of focused excitation of specific plasmon modes [15]. So far, for this reason, a mean of terahertz emission/detection utilizing photoexcited plasmon-resonance has been investigated [21–28].

2D plasmon itself is a non-radiative mode so that a metal-wired grating coupler structure is frequently utilized to yield terahertz electromagnetic-wave emission [8,10,12,14,15,26–30]. Wilkinson et al., studied far-infrared response of plasmon excitation from bi-periodically modulated 2D-electron gas coupled with doubly-interdigitated grating gates [10]. We have recently proposed and analytically characterized a terahertz emitter/photomixer device incorporating similar grating-bicoupled periodic plasmon-resonant structure together with an original vertical resonant-cavity enhanced structure [26,27].

This paper describes the design and performance of our firstly fabricated original terahertz plasmon-resonant emitter incorporating doubly interdigitated grating gates and a vertical cavity into an InGaP/InGaAs/GaAs high-electron mobility transistor (HEMT) structure. The fabricated device is subjected to 1550-nm wavelength lasers at room temperature in three different manners: (a) a single continuous-wave (CW) laser, (b) 4-THz photomixed dual CW lasers, and (c) a 70-fs pulsed laser. In case of (a), terahertz emission due to the plasmon modes of self oscillation is detected by a 4-K cooled Si bolometer. In case of (b), a resonant peak of injection-locked 4-THz oscillation is observed on the device photoresponse. In case of (c), an impulsive radiation followed by relaxation oscillation is observed by electrooptic sampling. Its Fourier spectra reflecting the plasmon modes are discussed in relation to the device structure.

2. Plasmon-resonant emitter

2.1. Device structure and operation principle

Fig. 1 illustrates the cross section of the plasmon-resonant emitter. The device structure is based on a HEMT and incorporates (i) doubly interdigitated grating gates (G1 and G2) that periodically localize the 2D plasmon in stripes on the order of 100 nm with a micron-to-submicron interval and (ii) a vertical cavity structure in between the top grating plane and a terahertz mirror at the backside. The terahertz mirror is a transparent metal like indium titanium oxide (ITO) making the plasmon excitation by optical photon irradiation from outside the back surface. As is shown in Fig. 7 in [26] the structure (i) works as a terahertz antenna and (ii) works as an amplifier.

Suppose that the grating gates have geometry with 300-nm G1 fingers and 100-nm G2 fingers to be aligned alternately with a space of 100 nm and that an appropriately high 2D electronic charge ($\sim 10^{12}\,\mathrm{cm}^{-2}$) is induced in the plasmon cavities under G1 while the regions under G2 are weakly charged (10^{10}–$10^{11}\,\mathrm{cm}^{-2}$). It is numerically simulated based on a self-consistent drift–diffusion Poisson equations that a strong electric field (1–10 kV/cm) arises at the plasmon cavity boundaries. When the device is photoexcited by laser irradiation, photoelectrons are predominantly generated in the weakly-charged regions with many unoccupied electronic states under G2 and then are injected to the plasmon cavities under G1. If a specific drain-to-source bias is applied to promote a uniform slope along the source-to-drain direction on the energy band in the regions under G2, photoelectrons under G2 are unidirectionally injected to one side of the adjacent plasmon cavity. This may excite the plasmons under an asymmetric cavity boundary [13,25]. It is noted that the laser irradiation may excite the plasmon not only in the regions under G1 but also in the regions under G2 if the cavity size and carrier density of the regions under G2 also satisfies the resonant conditions. The grating gates act also as terahertz antenna that converts non-radiative longitudinal plasmon modes to radiative transverse electromagnetic modes.

Once the terahertz electromagnetic waves are produced from the seed of plasma waves, downward-propagating electromagnetic waves are reflected at the mirror back to the plasmon region so that the reflected waves can directly excite the plasmon again according to the Drude optical conductivity and intersubband transition process [26]. When the plasmon resonant frequency satisfies the standing-wave condition of the vertical cavity, the terahertz electromagnetic radiation will reinforce the plasmon resonance in a recursive manner. Therefore, the vertical cavity may work as an amplifier if the gain exceeds the cavity loss. The quality factor of the vertical cavity is relatively low as is simulated in [26] since the 2D plasmon grating plane of one side of the cavity boundary must have a certain transmittance for emission of radiation. Thus, the cavity serves a broadband character.

According to the Mikhailov formulae of Eqs. (53) and (59) in [14] for the conditions of amplification of far-infrared radiation by means of DC-current-driven instability of grating-coupled 2D plasmons, the threshold velocity is still too high to perform room-temperature operation where electron drift mobility of the order of $10^5\,\mathrm{cm}^2/\mathrm{V\,s}$ is required even for idealistic III–V material systems. Photoexcitation in the periodically confined 2D plasmon grating structure of our proposal is expected to accelerate the instability, leading to room-temperature operation.