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Monte Carlo Analysis of Optical Pulse Response of Plasmon-Resonant Terahertz Emitter

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1. Introduction

The application of terahertz (THz) waves to engineering, e. g., imaging, information and communication technologies, has been investigated. Developing compact, tunable, and coherent sources that operate at THz frequencies is essential for innovation in these fields. We have found that THz emitters based on the plasmon resonance meet the requirements [1-2]. To enhance the THz emission power caused by inherent gain, we previously described a plasmon-resonant THz emitter with a dual-grating-gate high-electron-mobility transistor (HEMT) structure [3]. The THz radiation from the emitter was measured by using reflective electro-optic sampling (REOS) [4] and a Si bolometer [5]. In addition to the experimental demonstrations, theoretical work is needed to elucidate the physical mechanism of THz emission. We report the first simulation results using Monte Carlo analysis of optical pulse responses for our proposed plasmon-resonant THz emitter.

2. Device structure and operation principle

A cross section of our THz emitter [3] is shown in Fig. 1. The key features of the emitter are doubly interdigitated grating gates (G1 and G2) and a vertical cavity structure between the top grating plane and a terahertz mirror at the back. The dual-grating gates periodically localize the two-dimensional (2D) plasmon in stripes (plasmon cavities), which are of the order of 100 nm, with micron-to-submicron intervals. When an optical pulse illuminates the emitter, the electrons generated under the negatively-biased gates (for example G2) are asymmetrically injected into the adjacent plasmon cavities (under G1). This injection may also excite plasmons in the plasmon cavities. A 15-nm thick undoped $In_{0.2}Ga_{0.8}As$ layer was used for the 2D plasmon layer. A 60-nm thick $In_{0.48}Ga_{0.52}P$ layer with a 17-nm carrier-supplying layer acts as a barrier.

3. Simulation model

The unit structure shown in Fig. 1 was analyzed to find a way to reduce the memory size and computation time of the emitter. To obtain steady-state solutions, we numerically solved Poisson and current continuity equations for electrons and holes within the drift-diffusion approximation. Twenty thousand particles were placed in accordance with the steady-state electron distribution, and then Monte Carlo analysis [6] coupled with Poisson's equation calculation was performed. A 70-fs (FWHM) optical pulse was illuminated. Particles were assumed to be generated in the InGaAs layer under the negatively-biased gates (G2). Conventional scattering processes were included in the Monte Carlo simulations [6]. The Ramo-Shockley theorem was used to calculate the electron current induced on the electrodes (both sides of the analyzed region). Three simulation runs with different initial random numbers were carried out to remove numerical errors. For comparison, a conventional HEMT was also analyzed with the same method.

4. Result

Snapshots of particle energy distributions and electron concentration in the InGaAs layer are shown in Fig. 2. The gate lengths L_{G1} and L_{G2} were 100 and 300 nm, and the gate bias V_{G1} and V_{G2} were 0 and -1.5 V, respectively. A clear modulation of electron concentrations caused by the electric field was observed. Transient current responses were Fourier-transformed to obtain frequency responses. The current spectra simulated for the HEMT and THz emitter along with THz spectra measured with REOS [7] are shown in Figs. 3(a) and 3(b), respectively. The simulated spectra were in good agreement with the measured ones. The frequency response for HEMT monotonously decreased as the frequency increased. Peaks can be distinguished for the THz emitter. These peaks may have been caused by the oscillatory motion of electrons in the plasmon cavities and its harmonics. The conditions needed for plasmons to self-excite will be examined using the present simulation method to fully elucidate the emitter operation.

5. Conclusion

We have simulated the optical pulse responses for a plasmon-resonant THz emitter using the Monte Carlo method. The simulated Fourier spectra for our THz emitter and a conventional HEMT were in good agreement with those measured with reflective electro-optic sampling. The Monte Carlo simulation results show that there is a distinguished difference between the Fourier spectra measured for these devices. This analysis method will be a powerful tool for elucidating the operation of THz emitters.

Acknowledgment

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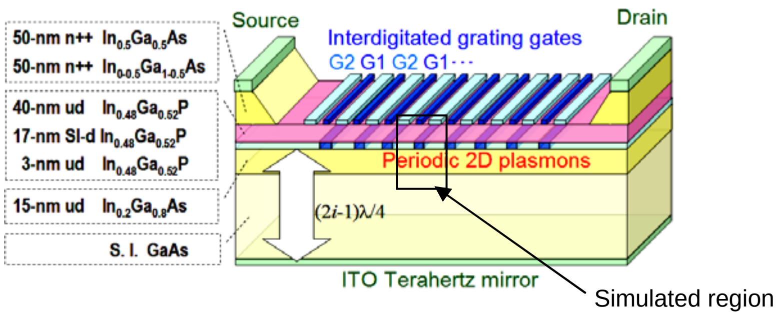

Fig. 1. Cross section of plasmon-resonant THz emitter.

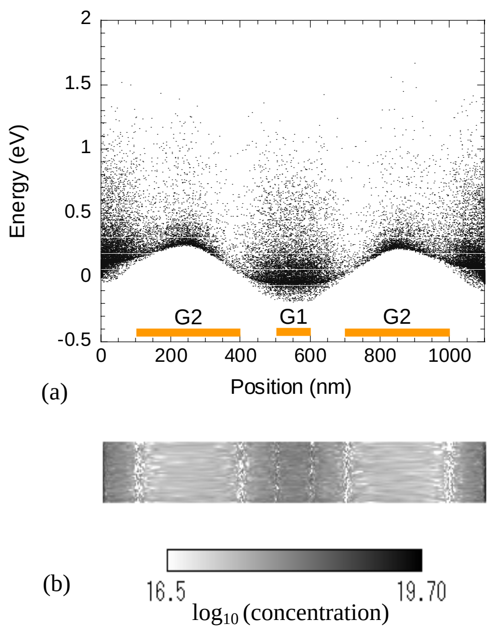

Fig. 2. (a) Particle energy distribution at 2 ps.
(b) Electron concentration in InGaAs layer.
(Vertical scale is enlarged.)

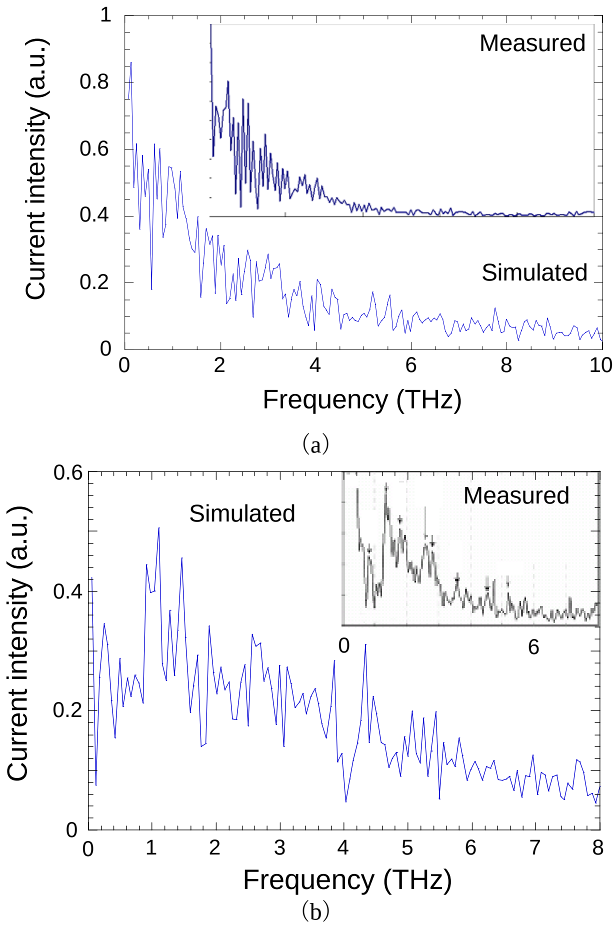

Fig. 3. Frequency responses of (a) HEMT and (b) THz emitter.