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Resonant terahertz photomixing in integrated HEMT-QWIP device

Victor Ryzhii[1], Maxim Ryzhii[1], Irina Khmyrova[1], Taiichi Otsuji[2], and Michael S. Shur[3]

Comp. Solid State Physics Lab, Univ. of Aizu, Aizu-Wakamatsu 965-8580, Japan
Phone:+81-242-37-2563, E-mail: v-ryzhii@u-aizu.ac.jp
[2] Research Inst. Electron Communication, Tohoku University, Sendai 980-8577, Japan
[3] Dept. of ECS Eng., Rensselaer Polytechnic Inst., Troy 12180, USA

1. Introduction

The channel of a high-electron mobility transistor (HEMT) acts as a resonant cavity for electron plasma waves [1]. The excitation of standing plasma waves in HEMTs leads to the oscillations of charges in the HEMT contacts and an antenna connected to these contacts. This results in the emission of THz radiation. The resonant excitation of plasma oscillations in HEMT-like heterostructures by incoming optical signals (photomixing) is considered as rather promising method of the generation of THz radiation [1-5]. Relatively strong response of quantum well infrared photodetectors (QWIPs) in the THz range due to the velocity overshoot of just photoexcited electrons [6] indicates that resonant properties of HEMTs and a fast response of QWIPs can provide an effective THz photomixing utilizing middle or far infrared signals. In this paper, we propose and assess a resonant THz photomixer based on a HEMT (serving as a resonant cavity) and a QWIP (working as a portion of the device absorbing infrared signals).

2. Device structure and operation principle

The device structure is shown schematically in Fig. 1. The electron channel in the HEMT portion of the device is formed at the heterointerface between an undoped narrow gap (for example, GaAs) layer and a wide gap (for example, AlGaAs) doped gate layer. The channel is supplied with a side contact (HEMT source). Another side contact region (HEMT drain) serves as the emitter of the QWIP. The QWIP portion of the device consists of a multiple QW structure (AlGaAs-GaAs). Either the inter-QW barrier layers or QWs can be doped. The dc bias voltages, $V_g \geq 0$ and $V_c > V_g$, are applied between the source and gate and the source and collector.

When the QWIP is irradiated with infrared radiation with the photon energies exceeding the QW bound energy, the electrons bound in QWs are photoexcited above the inter-QW barrier and propagate to the collector of the QWIP. These electrons induce the current in the HEMT channel. Under the transient irradiation (infrared radiation from two lasers with close photon frequencies or infrared pulse) the current induced in the HEMT channel is also transient. The latter leads to the excitation of plasma oscillation in this channel. Let us assume that the intensity (photon flux) of transient infrared radiation comprises the dc and ac components: $I(t) \simeq I_0 + I_\omega \exp(-i\omega t)$, where ω is the signal frequency. In the case of photomixed laser beam, $\omega = \Omega_1 - \Omega_2$. Here Ω_1 and Ω_2 are the photon frequencies which are chosen to be such that the photon energies $\hbar\Omega_1$ and $\hbar\Omega_1$ exceed the QW ionization energy Δ_i. The values I_0 and I_ω are determined by the photon fluxes of infrared radiation, I_1 and I_2, emitted by both lasers: $I_0 = I_1 + I_2$ and $I_\omega = 2\sqrt{I_1 I_2}$.

2. HEMT-QWIP characteristics

Using the hydrodynamic equations coupled with the Poisson equation for the self-consisted potential and calculating the ac current, J_ω^{sc},induced in the source-collector circuit , one can arrive at the following formula

$$J_\omega^{sc} = \frac{J_\omega}{\cos[\pi\sqrt{\omega(\omega + i\nu)}/2\Omega]}. \tag{1}$$

Here $\Omega = \pi s/2L_g$ is the characteristic plasma frequency, ν is the frequency of electron collisions in the HEMT channel and $s = \sqrt{e^2\Sigma_0/mC} = \sqrt{e(V_g - V_{th})/m}$ is the characteristic plasma wave velocity, where e and m are the electron charge and effective mass, Σ_0 is the dc sheet electron concentration in the HEMT channel (controlled by the gate voltage, V_g, and by the doping which determines the threshold voltage V_{th}), L_g is the gate length, and C is the capacitance per unit area of the HEMT channel. The quantity J_ω is the ac current in the QWIP generated by infrared signal (ac photocurrent). The ac photocurrent across the QWIP is given by

$$J_\omega = \hbar\Omega_1 D R_\omega I_\omega, \tag{2}$$

where R_ω is the QWIP frequency-dependent responsivity and D is the size of the QWIP. In the THz frequency range, the QWIP frequency-dependent responsivity can be evaluated either analytically or found using ensemble Monte Carlo particle method. Introducing the frequency-dependent responsivity of a HEMT-QWIP photomixer, $\mathcal{R}_\omega = J_\omega^{sc}/\hbar\Omega_1 D I_\omega$, and using eq. (1), we obtain:

$$\mathcal{R}_\omega = \frac{R_\omega}{\cos[\pi\sqrt{\omega(\omega + i\nu)}/2\Omega]}. \tag{3}$$

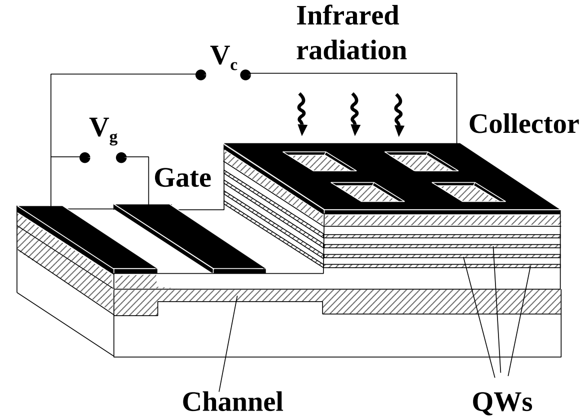

Figure 1: Schematic view of HEMT-QWIP photomixer.

Equation (3) shows that the HEMT-QWIP responsivity as a function of the signal frequency exhibits a pronounced resonant behavior if $\nu \ll \Omega$. Its absolute value reaches maxima at $\omega \simeq (2k-1)\Omega$, where $k = 1, 2, 3, ...$ is the resonance index. In the HEMTs with sufficiently short gate, the plasma frequency Ω can be in the THz range. Indeed, assuming the conventional value $s = 10^8$ cm/s, for HEMTs with $L_g = 0.25$ μm, one obtains $\Omega/2\pi = s/4L_g = 1$ THz.

Figure 2 shows the frequency-dependent responsivity, R_ω, of AlGaAs-GaAs QWIPs (with the spacing between QWs $L = 35$ nm, number of QWs $N = 4-64$, and average dc electric field $E = 40$ kV/cm) calculated using an ensemble Monte Carlo particle technique [6], and the frequency-dependent responsivity of an AlGaAs-GaAs HEMT-QWIP photomixer, $\mathcal{R}_\omega$, calculated using the obtained values of R_ω and eq. (3). The following parameters of the HEMT portion of the device are used: $\Omega/2\pi = 1$ THz and $\nu \simeq (2-10) \times 10^{11}$ s^{-1}. The latter corresponds to the electron mobility in the HEMT channel $\mu \simeq (3-15) \times 10^4$ cm^2/V·s. One can see that the HEMT-QWIP responsivity exhibits fairly sharp resonant maxima in the vicinity of the plasma frequency and its odd-numbered harmonics and the peak values of the HEMT-QWIP responsivity significantly exceed the QWIP responsivity.

The THz power, P_ω, generated by the device irradiated by two lasers with total power P_{infra} can be estimated as

$$P_\omega = r_a \mathcal{R}_\omega^2 P_{infra}^2, \qquad (4)$$

where r_a is the antenna radiation resistance. For the fundamental plasma resonance ($\omega \simeq \Omega$) at $P_{infra} = 5$ mW, $r_a = 100$ Ω, $\Omega/2\pi = 1$ THz, $\nu \simeq 2 \times 10^{11}$ s^{-1}, and $R_\omega = 0.01$ A/W, one can obtain $P_\omega \simeq 0.5$ mW.

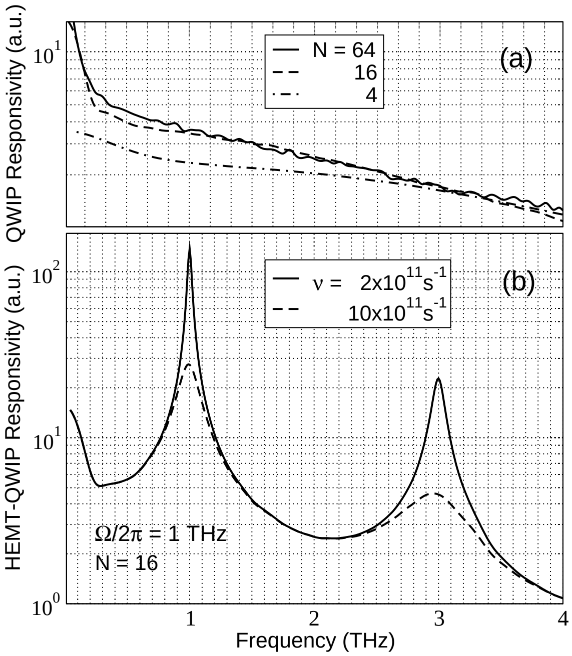

Figure 2: Frequency-dependent responsivities of (a) QWIPs with different numbers of QWs and (b) a HEMT-QWIP photomixer with 16 QWs.

3. Conclusions

We have proposed and assessed a resonant HEMT-QWIP photomixer. It have been demonstrated that the HEMT-QWIP photomixer exhibits pronounced resonant behavior due to the excitation of THz plasma oscillations in the HEMT channel by the ac photocurrent generated in the QWIP by incident infrared signals. The device responsivity at the resonant frequencies can significantly exceed that of the QWIP providing essentially higher efficiency of conversion of infrared radiation into THz radiation.

References

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