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Plasma Effects in Lateral Schottky Junction Terahertz Detector: Models and Characteristics

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INTRODUCTION

Two-dimensional electron gas (2DEG) systems in both ungated and gated channels with sufficiently high mobility of electrons confined in the lateral directions can serve as resonant cavities for electron plasma waves in different devices. The resonant plasma effects in gated 2DEG systems similar to high-electron mobility transistors (HEMTs) can be used for detection, frequency multiplication and generation of terahertz (THz) radiation [1].

In this paper, we propose novel detectors of THz radiation based on heterostructures with a 2DEG channel and a lateral Schottky junction (LSJ), develop their device models, and calculate their characteristics (frequency-dependent detector responsivity as a function of the device structural parameters). The some devices utilizing lateral LSJs have been proposed and studied for more than decade for applications as detectors and varactors for frequency multiplication in the THz range. However, since the 2DEG channels with high electron mobility can exhibit pronounced resonant response at the plasma frequencies, LSJ resonant detectors (and some other devices, for example, such as frequency multipliers) can provide substantially higher detection responsivity at the signal frequencies coinciding with the resonant plasma frequencies. The proposed LSJ resonant detectors using nonlinearity of the LSJ current-voltage characteristic can also surpass the HEMT-like resonant detectors utilizing the hydrodynamic nonlinearity [1].

DEVICE STRUCTURES AND OPERATION

The LSJ device structures with ungated and gated 2DEG channel schematically shown in Figs. 1(a) and 1(b), respectively. The band diagram of the LSJ portion of the devices is shown in Fig. 1(c). These devices comprises an Ohmic contact serving as a source and a Schottky contact (drain or collector) forming LSJ. The latter plays the role of a nonlinear element providing the rectification of the THz signals (detection). The LSJ resonant detectors in question can be fabricated using heterostructures based on different III-V materials or nitrides.

It is assumed that apart from some biasing voltage V, an ac voltage $V_\omega \cos\omega t$ (created by incoming THz signals, which are received by an antenna) is applied between the source and drain. This voltage stimulates the excitation of the plasma oscillations (self-consistent oscillations of the electron concentration in the 2DEG channel and the electric field around it). At the signal frequency ω coinciding with or close to one of the plasma resonant frequency Ω_n ($n = 1, 2, 3, ..$ is the index of the plasma resonance), the amplitude of the ac potential drop across the depleted region of the 2DEG channel can be rather large. Due to a strong nonlinearity of the LSJ current-voltage characteristics, this can lead to large nonlinear (rectified) component of the net current.

DEVICE MODELS

Due to a relatively large electron concentrations in the device channel and relatively low frequencies of electron collisions with impurity in phonons, 2DEG can be described by hydrodynamic electron transport model (Euler's equation and continuity equation). The hydrodynamic equations should be supplemented by the 2D Poisson equation for the self-consistent electric potential. In the case of the devices with the gated 2DEG channel, this equation can be replaced by its simplified ver-

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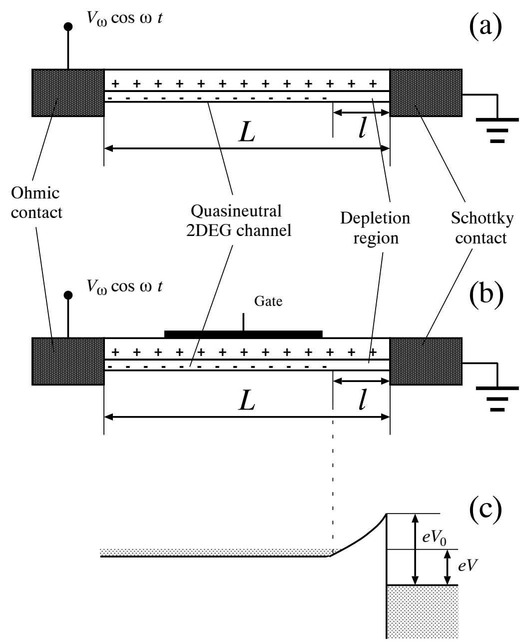

Fig. 1. Schematic view of LSJ resonant detectors with (a) ungated and (b) gated 2DEG channel; (c) band diagram of the device Schottky junction region with forward bias.

sion. The matching conditions at the point between the quasineutral and depletion regions in the 2DEG channel invoke simple expression for the LSJ current-voltage characteristic. Since the nonlinearity of the LSJ current-voltage characteristic is much stronger than that of the hydrodynamic equations, the linearized version of the latter can be used. More detailed models should account for hydrodynamic nonlinearities and specifics of nonequilibrium nonstationary transport in the high-electric field depletion region (combined hydrodynamic and ensemble Monte-Carlo particle models).

RESULTS

Using the model based on a simplified description of the electron transport in the 2DEG channel, one can obtain the following equation for the LSJ resonant detector responsivity:

$$R_\omega = \frac{2R_\omega^{SJ}}{[\cosh(\pi\nu/2\Omega) + \cos(\pi\omega/\Omega)]}, \qquad (1)$$

where R_ω^{SJ} is the responsivity of LSJ without excitation of plasma oscillations in the 2DEG channel, ν is the electron collision frequency. The frequency of fundamental plasma resonance is given by $\Omega \propto \sqrt{\Sigma_0/L}$ and $\Omega \propto \sqrt{\Sigma_0 W_g/L_g^2}$ for ungated and gated 2DEG channels, respectively, Σ_0 is the dc electron sheet concentration in the channel, L is the length of the channel, $L_g < L$ and $W_g \ll L$ are the gate length and the gate layer thickness. It is assumed that the length of the LSJ depletion region $l \ll L_g, L$. As seen from Eq. (1), the responsivity $|R_\omega|$ reaches maxima at the plasma resonant frequencies: $\omega = \Omega_n$, where $\Omega_n = (2n-1)\Omega$. The responsivity maxima are fairly high when $\nu \ll \Omega$:

$$max\left|\frac{R_\omega}{R_\omega^{SJ}}\right| \simeq \left(\frac{8}{\pi^2}\right)\left(\frac{\Omega}{\nu}\right)^2 \gg 1. \qquad (2)$$

The fundamental plasma frequencies for the devices with both ungated and gated 2DEG channels fall into the THz range at real device structural parameters. For fairly typical parameters $\Omega/2\pi = 1$ THz and $\nu = (5-10)\times 10^{11}\mathrm{s}^{-1}$, one obtains $max|R_\omega/R_\omega^{SJ}| \simeq 32 - 128$. In the devices with the gated 2DEG channel, the gate-drain voltage V_g can be applied to control the electron concentration under the gate $\Sigma_0 = \Sigma_0(V_g)$ and, hence, the resonant plasma frequencies.

The comparison of the responsivity of the LSJ resonant detector with the gated 2DEG channel under consideration (R_ω) with that based on the HEMT and utilizing the hydrodynamic nonlinearity (R_ω^{HEMT}) results in

$$max\left|\frac{R_\omega}{R_\omega^{HEMT}}\right| \simeq \left(\frac{s}{v_T}\right)^2 \gg 1. \qquad (3)$$

Here $s \propto \sqrt{\Sigma_0 W_g}$ is the characteristic plasma wave velocity and v_T is the thermal electron velocity in the 2DEG channel. Usually, $s/v_T \simeq 10$, so that $max|R_\omega/R_\omega^{HEMT}| \simeq 10^2$.

CONCLUSION

We proposed novel THz detectors based on heterostructures with LSJ, developed their models and assessed the device characteristics. It was shown that the devices proposed can substantially surpass those studied previously. Numerical studies using more detailed and complex device models are necessary.

REFERENCES

[1] M. Dyakonov and M. Shur, *Detection, mixing, and frequency multiplication of terahertz radiation by two dimensional electronic fluid*, IEEE Trans. Electron Devices **43**, 1640 (1996).