Dependence of the resonant frequency on the gate voltage in grating-gate structures

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***Abstract*—Compact and tunable devices is a long-range challenge for THz nanoelectronics. One of the advantages of field-effect transistor (FET) based THz devices prototypes is the operating frequency range of several terahertz. The famous dependence of plasmonic resonance frequency on gate voltage $\omega \propto \sqrt{U_g - U_{th}}$ is valid for single FETs. However, grating-gate structures show different dependence. The grating creates two dimensional electron system with periodic modulation of electron concentration. We show and describe function dependence of natural frequency on plasmonic velocity in gated region.**

***Index Terms*—THz nanoelectronics, plasma waves, plasmonics, plasmonic crystal, Kronig-Penney model.**

I. Introduction

FEILD-EFFECT transistors (FETs) are promising candidates for THz devices, in particular detectors [1]. And the grating-gate structures show better coupling with THz radiation than single FETs [2]. Recent experiments show unusual properties of grating-gate plasmonic structures and the theoretical investigation is required.

To describe the electron liquid in FET linearized hydrodynamic equations are used. Kronig-Penney model allows to obtain the dispersion equation of plasma waves in periodic potential.

Grating gate creates potential with period $L_1 + L_2$ which consists of ungated and gated regions with length L_1 and L_2 correspondingly. The dispersion equation for grating gate structure is as follows [3]:

$$\cos\Omega_1 \cos\Omega_2 - \frac{q_1^2 + q_2^2}{2q_1 q_2} \sin\Omega_1 \sin\Omega_2 = \cos\left[K(L_1 + L_2)\right],$$

where $\Omega_i = q_i L_i$ and q_i is wave vector. It describes natural frequencies of 1D plasmonic crystal with alternating regions of length L_1 and L_2 with different plasma wave velocities s_1 and s_2. Dependence $\Omega_1(s_2)$ is not expressed in analytical functions in general case.

If we neglect the decay rate and consider the external wavelength to be large, then the dispersion equation simplifies:

$$\cos\frac{\omega L_1}{s_1} \cos\frac{\omega L_2}{s_2} - \frac{s_1^2 + s_2^2}{2s_1 s_2} \sin\frac{\omega L_1}{s_1} \sin\frac{\omega L_2}{s_2} = 1 \tag{1}$$

The region of length L_1 with constant plasma wave s_1 assumed ungated in contrast to region of length L_2 with voltage-dependent s_2.

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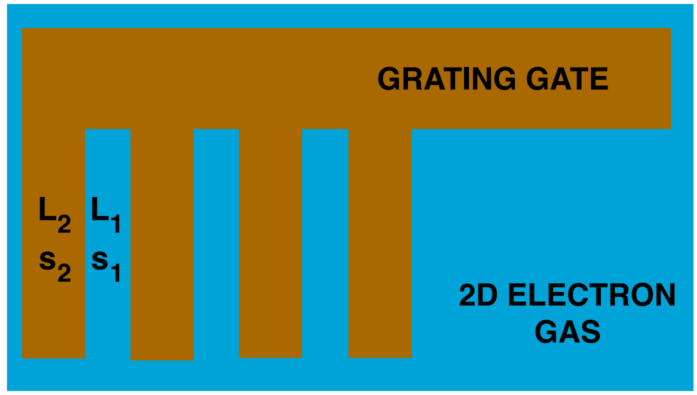

Fig. 1. Sketch of grating-grate FET with alternating two types of regions – ungated (length L_1 and plasmonic velocity s_1) and gated (length L_2 and plasmonic velocity s_2).

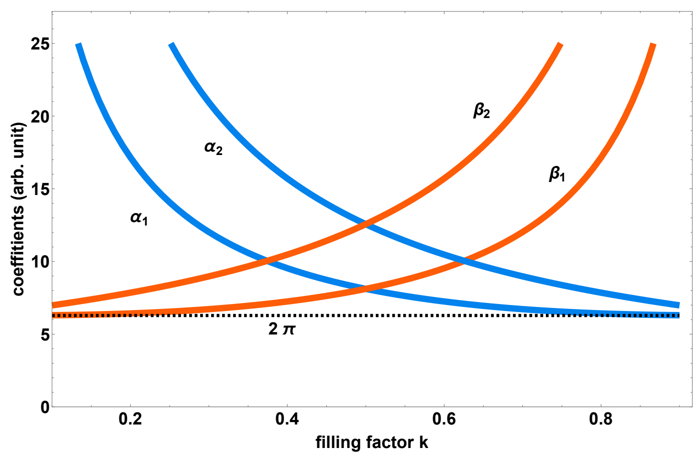

Fig. 2. Filling factor $k = L_2/(L_1 + L_2)$ dependence of first solutions $\alpha_{1,2}$ and $\beta_{1,2}$ coefficients corresponding to the first frequency branch.

II. Results

For small s_2 assuming $\omega \propto \alpha s_2/(L_1 + L_2)$ we find that α satisfies

$$\cos k\alpha - \frac{1-k}{2}\alpha \sin k\alpha = 1. \tag{2}$$

For large s_2 assuming $\omega \propto \beta s_1/(L_1 + L_2)$ we find that β satisfies

$$\cos(1-k)\beta - \frac{k}{2}\beta \sin(1-k)\beta = 1. \tag{3}$$

The multiple solutions α_N and β_N ($\alpha_i < \alpha_{i+1}, \beta_i < \beta_{i+1}$) can be found exactly for different gate filling factors $k = \frac{L_2}{L_1+L_2}$.

Let us discuss the 1^{st} natural frequency plasmonic branch.

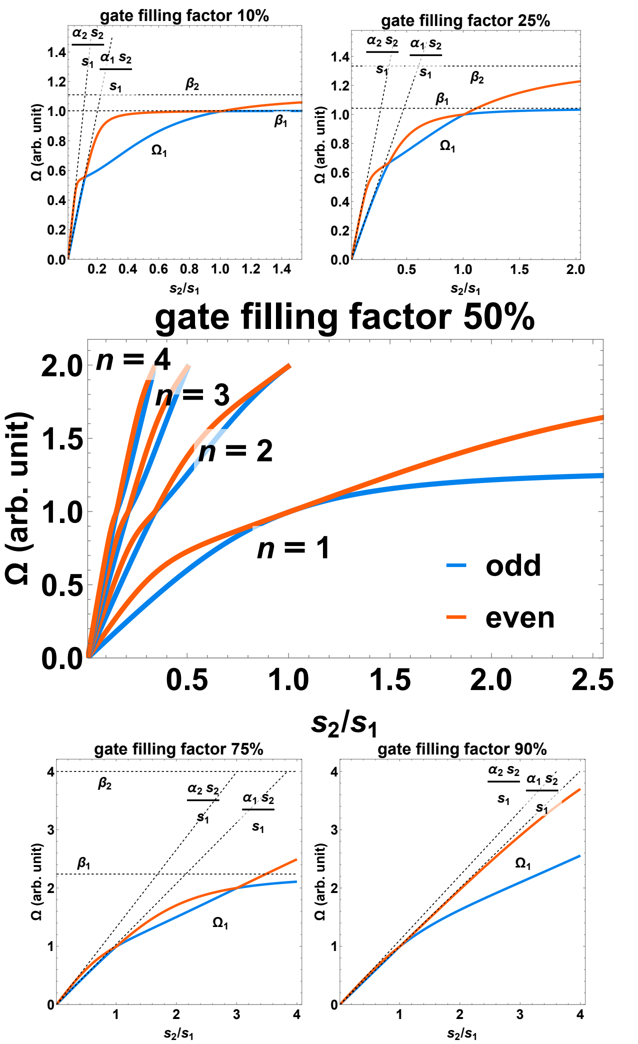

Fig. 3. First frequency branch $\Omega = \omega s_1/(L_1+L_2)$ depending on normalized plasma wave velocity s_2/s_1 for different values of filling factor $L_2/(L1+L_2)$

In FETs it is known that $\omega_1 = a\pi s/L$ where the value of coefficient a depends on BC: $a = 1/2$ for voltage fixed at the source and current fixed at the drain and $a = 1$ for voltage fixed both at the source and at the drain.

Can be found that for $k = 0.5$ $(L_1 = L_2)$ values $a \approx 2.61873$.

III. Conclusion

In this work we distinguished tangent lines delimiting a frequency on plasma wave velocity functions:

$$\omega = \alpha(k)s_2/(L_1+L_2),\ \omega = \beta(k)s_1/(L_1+L_2). \quad (4)$$

Usually $s_2 \propto \sqrt{U_g - U_{th}}$, so these to lines could help to analyze the experimental data for multi-gated structures.

Also, the exact solution of the dispersion equation shows that there are pairs of frequency branches in the plasmonic crystal, which coincide at $s_2 = s_1$ and, probably, are indistinguishable at a sufficiently low quality of the resonances.

Also let us notice that limiting case $L_1 \to 0$ (or $L_2 \to 0$), when grating-gate FET turns to single FET without with free boundary conditions.

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