Nonresonant Response Characteristics to Terahertz Radiation of FETs: Influence of Magnetic Field

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ABSTRACT

Nonresonant detection on terahertz radiation of field effect transistors by the influence of magnetic field is studied in this paper. The influence of the magnetic field upon the electron mobility in the transistor channel is discussed and the corresponding influence on the nonresonant detection photoresponse is analyzed in detail. Based on the work before, the numerical tool has been modified by adding the influence of magnetic field, and the nonresonant photoresponse characteristics are investigated. The result of simulation has verified the theory, and the work mechanism of this influence has been revealed in this paper.

Keywords: Terahertz, Magnetic, FETs, Nonresonant, Detection

1 INTRODUCTION

Detection of terahertz radiation of FETs is based on the hydrodynamic shallow water theory proposed by Dyakonov and Shur in 1993 [1]. External radiation and the asymmetry between source and drain contacts induce the detection response which is enhanced by an applied dc current in the transistor channel [2] [3]. Two detection modes in FETs are defined as resonant and non-resonant detection respectively. The resonant case is correlated to the excitation of discrete plasma modes in the channel. In the mechanism of non-resonant detection, the plasma wave is overdamped [4-8].

Currently, the effect of magnetic field on the plasma wave excitation and detection of terahertz radiation have become an attracted topic. It is demonstrated that low magnetic field enhances the current instability in the transistor channel [9]. In high magnetic field, the conduction band splits to Landau levels, including SdH oscillation and cyclotron resonance which affect the detection responsivity dramatically [10-11]. In this paper, the magnetic effect on non-resonant response characteristics to terahertz radiation in FETs is investigated. Based on the nonresonant detection theory developed by W. Knap in 2002 [4], a new analytical photoresponse expression is derived. Further development is made by coupling the magnetic field in the program established by Xuehao Mou in 2008 [13]. Simulation on nonresonsant detection of terahertz radiation is investigated in consideration of vertical magnetic field.

2 THOERY ANALYSIS

Dyakonov and Shur proposed the hydrodynamic equations describing the electron fluid in FET channel. While the magnetic field is applied, the 2-D electron gas in a gated channel is described as [9-11]:

$$\frac{\partial v}{\partial t}+\left(v\cdot\nabla\right)v=-\frac{e}{m}\nabla U+\frac{e}{m}B\times v-\gamma v \qquad (1)$$

$$\frac{\partial U}{\partial t}+div(Uv)=0 \qquad (2)$$

where v is the electron drift velocity, B is the magnetic field along the z direction, m is the electron effective mass, $U(x,t)=U_{GC}(x,t)-U_T$, U_{GC} is the gate-to-channel voltage, and U_T is the threshold voltage. The parameter γ which causes SdH oscillations [11] depends on the electron concentration and magnetic field when $\gamma=1/\tau$. Here τ is the momentum relaxation time correlated to external friction induced by scattering of electrons by phonons or impurities.

Eq. (1) is the Euler equation, which is similar to Navier-Stocks equations in hydrodynamics. Lorentz force and damping of oscillations are taken into account while magnetic field is under consideration. Eq. (2) is the continuity equation. The general equation for the electron density in the FET channel is given by [4]:

$$n=n^{*}\ln\left[1+\exp(\frac{eU_0}{\eta k_B T})\right] \qquad (3)$$

where $n^* = C\eta k_B T / e^2$, and η is the ideality factor. When gate bias is positive and large enough ($U_0 > \eta k_B T / e$), the electron concentration is defined as $n = CU_0 / e$, where C is the surface gate capacitance [4].

The boundary conditions [3-8] of Eq. (1) and Eq. (2) are described as:

$$U(0) = U_0 + U_a \cos \omega t \tag{4}$$

$$\left[\frac{\partial n}{\partial x}\right]_{x=L} = -\frac{j_d}{\mu \eta T} \tag{5}$$

Where ω is the frequency of incoming radiation, U_a is the amplitude of the radiation-induced modulation of the gate-to-channel voltage.

For the nonresonant detection case, the term $\partial v / \partial t + (v \cdot \nabla) v$ in Eq. (1) is neglected under the condition of $\omega\tau << 1$. Accordingly, Eq. (1) and Eq. (2) become [4, 8]:

$$-\frac{e}{m}\nabla U + \frac{e}{m} B \times v - \gamma v = 0 \tag{6}$$

$$\frac{\partial U}{\partial t} + div(Uv) = \frac{j_0}{eL} \tag{7}$$

Consider the x and y direction respectively， we obtain:

$$\frac{d}{dx}\left(-\frac{eU}{m}\right) = v_y \omega_c + \frac{v_x}{\tau} \tag{8}$$

$$0 = -v_x \omega_c - \frac{v_y}{\tau} \tag{9}$$

where $\omega_c = eB/mc$, and $\tau = 1/\gamma$. ω_c is the cyclotron frequency [10-11].

Substituting (9) into (8), one gets:

$$-\frac{e}{m}\frac{dU}{dx} = \frac{\omega_c^2 \tau^2 + 1}{\tau} v_x \tag{10}$$

For

$$\mu_0 = \frac{e\tau}{m} \tag{11}$$

And

$$\mu(B) = \frac{e}{m} \cdot \frac{\omega_c^2 \tau^2 + 1}{\tau} \tag{12}$$

One obtains:

$$\mu(B) = \mu_0 \frac{1}{1 + \mu_0^2 B^2} \tag{13}$$

For zero magnetic field case, B=0, Eq. (13) simplifies to $\mu(B) = \mu_0$. Here μ_0 is the electron mobility in the transistor channel when the strength of the magnetic field is zero.

According to [4], the nonresonant detection photoresponse is obtained:

$$\Delta u = \frac{e{u_a}^2}{4mS^2} \left\{ \frac{1}{1 + k \exp\left(-\frac{eU_0}{\eta k_B T}\right)} - \frac{1}{\left[1 + k \exp\left(-\frac{eU_0}{\eta k_B T}\right)\right]^2 \left[sh^2 Q + \cos^2 Q\right]} \right\} \tag{15}$$

Where

$$\kappa = \frac{(j_0 - 2j_d) Lme}{2C\tau\eta^2 k_B^2 T^2} \tag{16}$$

$$Q = \frac{L}{S}\sqrt{\frac{wq\left(1 + {\mu_0}^2 B^2\right)}{2\mu_0 m}} \tag{17}$$

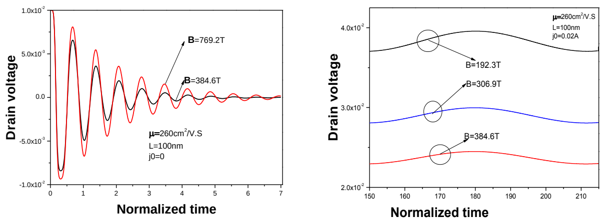
Eq. (15) to Eq. (17) illustrate that the magnetic field has an influence on the nonresonant detection photoresponse of terahertz radiation. The photoresponse Δu is inversely proportional to the magnetic field B.

3 RESULTS AND DISCUSSION

We have developed the work of Xuehao Mou [12] to the application in simulating the photoresponse by the influence of magnetic field. Different situations have been investigated by the developed numerical tool to analyze the influence of magnetic field, such as different work operations from the subthreshold to the strong inversion by varying values of gate voltage, different strength of magnetic field, et al. To testify the correctness of the proposed theory in this paper, both the simulation results and the analytical results are put together for comparison, and the results predict the characteristics of the response influenced by the magnetic field.

The numerical method is established by normalizing several variables as $n = n_s / n_{s0}$, $v = V / s$, $\eta = x / L$, $\tau = ts_t / L$, $\tau_m' = \tau_m s / L$, where V_t is defined as the thermal voltage, $s = \sqrt{eV_t / m}$. Thus, the hydrodynamic equations are simplified to the dimensionless form. A field effect transistor structure is used in our simulation with the given parameters, where the electron density in the channel is $n = 5 \times 10^{17} cm^{-3}$, the channel length is $100nm$, and the thickness of the oxide layer is $2nm$. The threshold voltage is 1.145V. The input terahertz signal u_a is 0.01V. In order to test the influence of magnetic field on the characteristics of nonresonant response, the product of electron mobility and magnetic field are defined as a variable changing from 0 to 2, with a step of 0.2.

Drain voltage versus normalized time is presented in Figure.1 to illustrate that the increase of magnetic field leads to the enhancement of oscillation magnitude of drain voltage which contains both dc component and ac signal. It is shown in Figure.1(a) that the dc component of drain voltage is extraordinarily small. In Figure.1(b), by applying the dc current to the FET channel, the dc component of drain voltage becomes larger. Figure.2 presents a 3D simulation result of drain voltage versus gate-to-source voltage and normalized time.



(a) (b)

Figure.1 Drain voltage (V) versus normalized time (a) j0=0 (b) j0=0.02A.

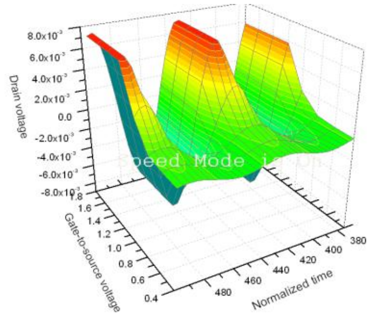
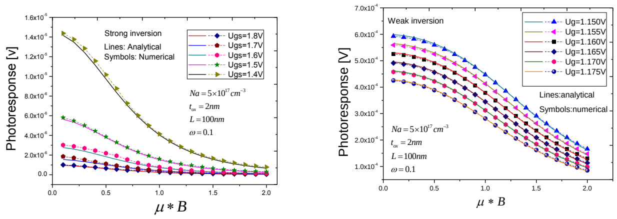


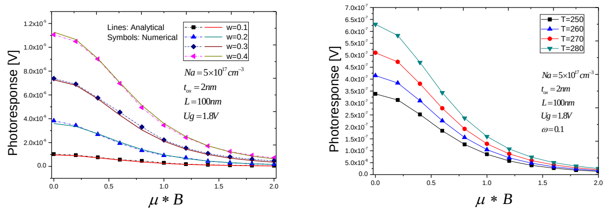
Figure. 2 Drain voltage (V) versus normalized time dc and gate-to-source voltage. Parameters used in the simulation are: $Na = 5\times10^{17} cm^{-3}$, $L = 100nm$, $t_{ox} = 2nm$, $T = 300K$

As is shown in the following figures, the lines are used to represent the analytical results and the numerical results are denoted by the symbols. The dependence of nonresonant response on magnetic field is given by Figure.3 and Figure.4. In Figure. 3, the responses in strong inversion region and in subthreshold region are presented respectively; it is shown that the nonresonant response is inversely proportional to magnetic field. In strong inversion region, the photoresponse drop is remarkable first and smooth later. The subthreshold case has a reverse variation tendency. The response in subthreshold region is found to be larger than that in strong inversion region by comparing the two Figures. The dependence of nonresonant response on temperature and frequency is predicted by Figure. 4. It is illustrated that higher temperature or frequency leads to higher response.



(a) (b)

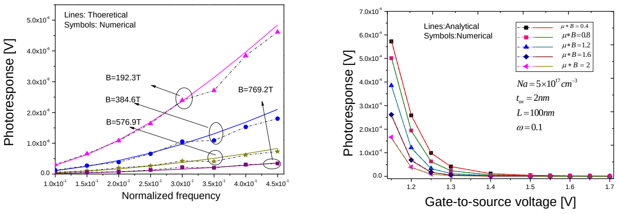
Figure.3 Photoresponse versus magnetic field for (a) strong inversion region (b) subthreshold region.



(a) (b)

Figure.4 Photoresponse versus magnetic field, (a) different frequency (b) different temperature

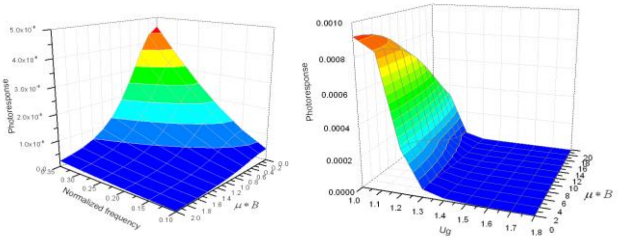
In Figure.5 (a), nonresonant response as a function of normalized frequency is given to show that the response is increased by an increasing frequency and by a decreased magnetic field. Figure.5 (b) illustrates that nonresonant response in subthreshold region is higher than that in strong inversion region. From the above figures, it is clear to see that the simulation results match the analytical results well, which verifies the correctness of the proposed analytical theory in this article.



(a) (b)

Figure. 5 (a): Photoresponse versus normalized frequency, (b): Photoresponse as a function of gate-source voltage.

3D simulations which show influences of magnetic field on magnetic field and frequency as well as gate-to-source voltage are given by Figure.6(a) and Figure.6(b).



(a) (b)

Figure. 6(a): Photoresponse (V) versus magnetic field and normalized frequency, (b)： Photoresponse (V) versus gate-to-source voltage and magnetic field. Parameters used in the simulation are: $Na = 5\times10^{17} cm^{-3}$, $L = 100nm$, $t_{ox} = 2nm$, $T = 300K$.

4 CONCLUSION

In this paper, the field effect transistor is used as a detector for terahertz radiation in a vertical magnetic field. An analytical theory on the non-resonant detection response is developed and discussed. Based on the numerical tool developed by coupling the magnetic field, the simulation of various characteristics correlated with non-resonant response from subthreshold region to strong inversion region are investigated. It is demonstrated that the nonresonant response is inversely proportional to magnetic field in both subthreshold region and strong inversion region. In sub-threshold region of FET, the influence of magnetic field is remarkable. Non-resonant response is enhanced by dc current applied to the FET channel.

5 ACKNOWLEDGEMENT

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REFERENCES

[1] M. Dyakonov and M. Shur, “Shallow Water Analogy for a Ballistic Field Effect Transistor: New Mechanism of Plasma Wave Generation by dc Current”, PHYS. REV. LETT., VOL. 71, NO. 15, 1993.

[2] Mikhail Dyakonov and Michael Shur, “Detection, Mixing, and Frequency Multiplication of Terahertz Radiation by Two-Dimensional Electronic Fluid,” IEEE Transactions on Electron Devices, Vol.43, No.3, 1996.

[3] D. Veksler, F. Teppe, A. P. Dmitriev, V. Yu. Kachorovskii, W.Knap, and M. S. Shur, “Detection of Terahertz Radiation in Gated Two-Dimensional Structures Governed by dc Current,” Physical Review B 73, 125328, 2006.

[4] W.Knap, V.Kachorovskii, Y.Deng, S.Rumyantsev, J.-Q.Lu, R.Gaska, and M.S.Shur, “Nonresonant Detection of Terahertz Radiation in Field Effect Transistors,” Journal of Applied Physics, Vol.91, No.11, 2002.

[5] M.I.Dyakonov and M.S.Shur, “Plasma Wave Electronics: Terahertz Detectors and Sources Using Two Dimensional Electronic Fluid in High Electron Mobility Transistors,” Frontiers in Electronics, WOFE '97. Proceedings, 1997.

[6] Jian-Qiang Lu and Michael S.Shur, “Terahertz Detection by High-Electron-Mobility Transistor: Enhancement by Drain Bias,” Applied Physics Letters, Vol.78, No.17, 2001.

[7] W.Knap, F.Teppe, Y.Meziani, N.Dyakonova, and J.Lusakowski, F.Boeuf, T.Skotnicki, D.Maude, S.Rumyantsev and M.S.Shur, “Plasma Wave Detection of Sub-Terahertz and Terahertz Radiation by Silicon Field-Effect Transistors,” Applied Physics Letters, Vol.85, No.4, 2004.

[8] Y.M.Meziani, J.Lusakowski, N.Dyakonova, W.Knap, D.Seliuta, E.Sirmulis, J.Devenson, G.Valusis, F.Boeuf and T.Skotnicki, “Non-Resonant Detection of Terahertz Radiation by Nanometer Field Effect Transistors,” Joint 30th Intl. Conf. on Infrared and Millimeter Waves & 13th Intl. Conf. on Terahertz Electronics, IEEE, 2005.

[9] M.S.Kushwaha and Vasilopoulos, Influence of a magnetic field on the current instability in a ballistic field-effect transistor, Physical Review B, Vol.64, 125320.

[10] Maria Lifshis, and Michel I. Dyakonov, “Photovoltaic effect in a gated two-dimensional electron gas in magnetic field,” arXiv: 0901. 2712v1 [cond-mat.mess-hall] 18 Jan 2009

[11] S.Boubanga-Tombet, M.Sakowicz, D.Coquillat, F.Teppe, W.Knap, “Terahertz Radiation Detection by Field Effect Transistor in Magnetic Field,” arXiv: 0904-2081

[12] Xuehao Mou, Yu Chen, Chenyue Ma, Yuchi Che, Jin He, “A Numerical Method to simulate THz-Wave Generation and Detection of Field-Effect Transistors,” Solid-State and Integrated-Circuit Technology, ICSICT, 2008.