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Enhanced Photoresponse of Plasmonic Terahertz Wave Detector Based on Silicon Field Effect Transistors with Asymmetric Source and Drain Structures

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Abstract—**We investigate the enhanced effects of asymmetry ratio variations of the source and drain area in silicon (Si) field-effect transistor (FET). Photoresponse according to the variation of asymmetry difference between the width of source and drain are obtained by using the plasmonic terahertz (THz) wave detector simulation based on technology computer-aided design (TCAD) with the quasi-plasma 2DEG model. The simulation results demonstrate the potential of Si FETs with asymmetric source and drain structures as the promising plasmonic THz detectors.**

Index Terms—**Asymmetry, photoresponse, terahertz wave detector, quasi-plasma 2DEG, TCAD simulation**

I. INTRODUCTION

Terahertz wave detectors have been much attracted for the applications in the fields of security sensing, biomedicine, and remote control [1-4]. THz detection using oscillations of channel plasma waves in a field-effect transistor (FET) structure have been reported [5-8]. Since the modulation and propagation of a plasma-wave electron fluid definitely depend on the plasmon decay time $\tau = \mu m/e$ (where μ is the carrier mobility, m is the effective mass of electron, e is the electron charge), the parameter $\omega\tau$ is called the resonance quality factor. Low frequency regime occurs when $\omega\tau < 1$, the FET operates in a nonresonant regime, but the rectification mechanism is still available and enables broadband THz detection even though the plasma oscillations are overdamped [9].

Recently, researches for the enhanced photoresponse (ΔU) have a lot of attention. A photoresponse appears in the form of dc voltage between source and drain which is proportional to the radiation power. Related articles reported with an asymmetric double-grating gate FET structure [10] and asymmetric effects of device parasitics by integrating antenna, FET rectifiers, and a voltage amplifier [11]. However, the research of induced charge asymmetry in the device structure itself has not been reported yet.

In this work, we report the enhanced photoresponse of plasmonic THz wave detector based on Si FET with asymmetry structure considering the source and drain width variation by using the physical simulation on TCAD framework.

II. MODELING OF PLASMONIC THZ DETECTOR

Fig. 1 shows the device simulation structures based on Si FET for the extraction of the photoresponse. Asymmetric structure condition is determined by the difference of width of source and drain and then, asymmetry ratio(η_a) under the gate electrode can be defined by $\eta_a = W_D/W_S$.

Fig. 2 shows that the modulations of the channel 2DEG density at 0.7 THz have been successfully

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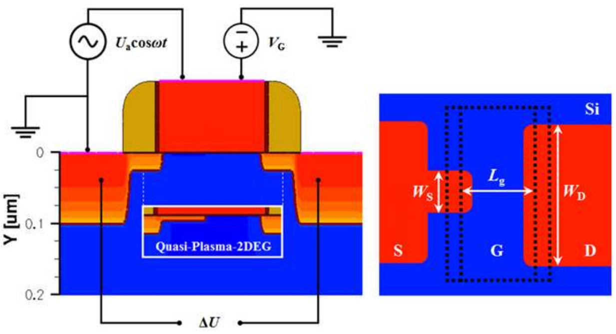
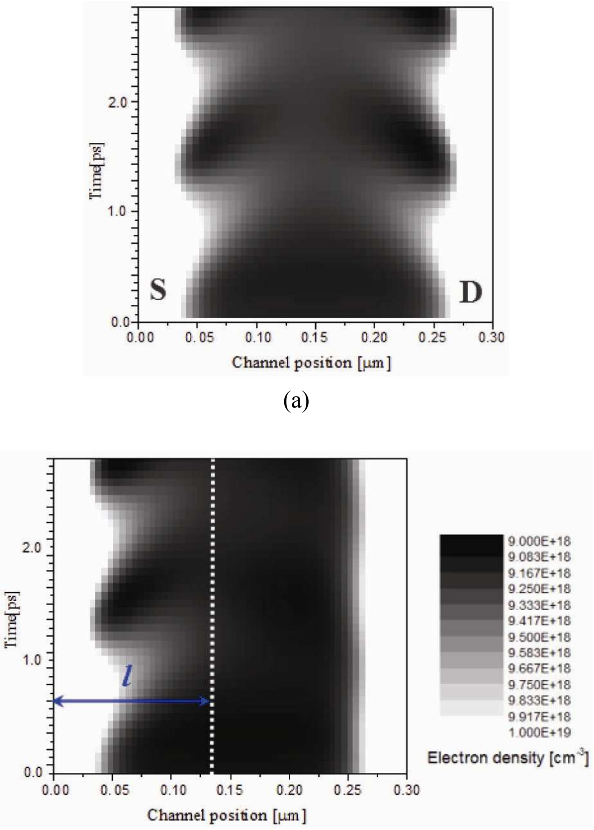


(a) (b)

Fig. 1. Simulation structure based on Si FET (a) THz detector structure and circuit configuration, Both DC and AC voltage source are applied to the gate terminal to control the channel 2DEG density and source to the ground. Inset shows the quasi-plasma electron box as 2DEG in the channel region, (b) Top view of structure with design parameters. W_S and W_D will be varied in simulation and L_g is fixed in 300 nm.



(a)

(b)

Fig. 2. Contour plot of the channel electron density modulation along with the channel position at each time scale. The channel 2DEG density is modulated near source and drain side due to the incoming THz radiation with f=0.7 THz (a) Symmetric structure (C_{GD}=C_{GS}), (b) asymmetric structure (C_{GD}>C_{GS}).

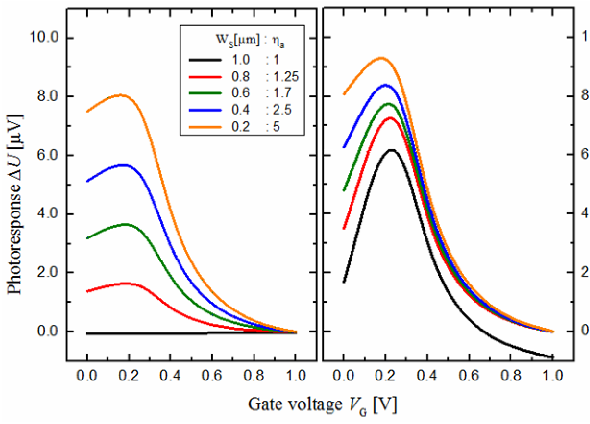
obtained through the transient simulation based on the coupled Drude and continuity equation, which are readily implemented in the TCAD framework. These contour plots of the channel 2DEG density modulation along with the channel position at each time scale depend on the symmetric or asymmetric condition between C_{GS} and C_{GD} as shown in Figs. 2(a) and (b), which indicate the symmetry (C_{GS}=C_{GD}) and asymmetry (C_{GD} > C_{GS}), respectively, in source and drain boundary condition given by C_{GS} and C_{GD}. In case of asymmetric situation, the AC signal has been applied only at the source side (x= 0) as $V(0, t)$= 0.05sin(ωt) + 0.3 V and gate-to-drain voltage can be kept with DC gate voltage as $V(L, t)$= 0.3 V at x= L. As shown in Fig. 2(b), the plots of electron density have been successfully obtained through the transient simulation. The propagation distance (l) and density of the modulated 2DEG can be estimated as 130 nm and 1 x 10^{19} cm^{-3}, respectively, which provide the physical length and density of the quasi-plasma 2DEG.

III. SIMULATION RESUTLS AND DISCUSSION

1. Methodology by Quasi-plasma 2DEG

Fig. 3 shows the photoresponse simulation results as a function of gate voltage according to the variation of asymmetry ratio when W_D is fixed with 1 μm while W_S is varied from 1 μm to 0.2 μm. Fig. 3(a) shows when photoresponse can be extracted by asymmetry ratio of between the W_D and the W_S without 2DEG, In case of the photoresponse simulation without quasi-plasma 2DEG, as shown in Fig. 3(a), it is hard to observe the difference of voltage (ΔU) in the symmetrical structure (η_a= 1). In Fig. 3(b), however, the simulation results by incorporating quasi-plasma 2DEG into channel region clearly show the significant photoresponse can be obtained under the asymmetric boundary condition which was created by radiation of THz wave. It should be noted that the simulation result with quasi-plasma 2DEG can explain the previous experimental data to show photoresponse before threshold voltage even in the symmetrical structure [7, 8].

In terms of expected improvement, we pointed out from our previous work [12] that there is the optimized operation window regarding with a single operation gate DC voltage both for the responsivity R_V = ΔU /P_a (V/W) where the actual power P_a [8] and noise equivalent power NEP = N/R_V (W/Hz$^{0.5}$) where N = $(4kTR_d)^{0.5}$ is the



(a) (b)

Fig. 3. Photoresponse to 0.7 THz radiation as a function of the gate voltage for Si FETs (a) without 2DEG, (b) with 2DEG. The W_S splits from 1.0 μm to 0.2 μm and the corresponding asymmetry ratio η_a is from 1 to 5.

thermal noise of FET at room temperature, which are the two typical performance metrics of nonresonant THz detector. During the NEP calculation procedure, the channel resistance R_d for the thermal noise was extracted from DC I-V characteristics of FETs, and thus, the basic DC characteristics should be considered significantly for the performance prediction and evaluation of FET-based plasmonic THz detectors as well.

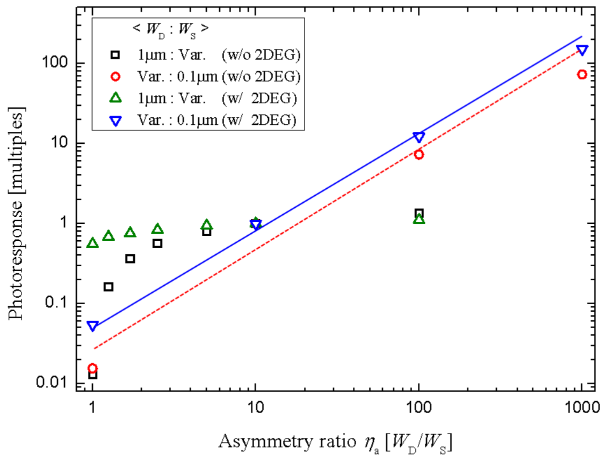
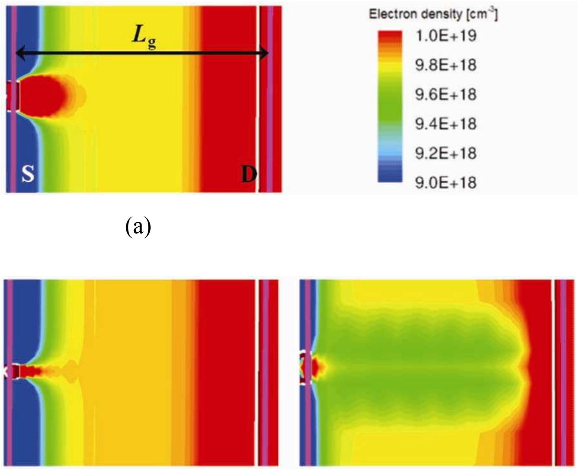


Fig. 4. The photoresponses according to asymmetry ratio with and without the 2DEG. When 10 of asymmetry ratio is set to be a reference, others are multiples of it. The solid blue line and dashed red line are linear fits of plots of reverse triangle and circle symbol data, respectively.



(a)

(b) (c)

Fig. 5. Top view of 2-D electron density plot in the channel region of Si FET without quasi-plasma 2DEG from 3-D device simulation (a) W_D is 1 μm and W_S is 0.1 μm (η_a= 10), (b) W_D is 1 μm and W_S is 0.01 μm (η_a = 100), (c) W_D is 10 μm and W_S is 0.1 μm (η_a = 100).

2. Enhanced Photoresponse by Asymmetry Ratio

Fig. 4 shows the photoresponse increment ratio with multiples according to the asymmetry ratio both cases of simulation with and without quasi-plasma 2DEG. The reference of the photoresponse is set to be the value at the asymmetry ratio η_a= 10 and then, all the other values have been represented by the multiples of it. It can be noted that there are two different tendencies of photoresponse increment regarding the device dimension. When the W_D is fixed and the W_S is decreased to increase asymmetry ratio, the tendency of photoresponse increment is saturated since the source width is extremely reduced. If the W_D is increased to increase asymmetry ratio while the W_S is fixed, however, the photoresponse is increased more linearly since the significant charge asymmetry occurs as the geometric device size grows asymmetrically. From the results of Fig. 4, it can be noted that photoresponse is closely related with drain area depending on the W_D. Figure 5 shows 2-D electron density plot in the channel area (top view) between source and drain with various W_D and W_S. In comparison with reference asymmetric device with η_a= 10 where W_D = 1 μm and W_S= 0.1 μm (Fig. 5(a)), the photoresponse of device with η_a= 100 where W_D = 1 μm and W_S= 0.01 μm (Fig. 5(b)) has been enhanced about 1.5 times as shown in Fig. 4. This enhancement of photoresponse can be explained in terms of the propagation distance (l) for more asymmetric structure of

Fig. 5 (b) than Fig. 5 (a). As simplified theory of the plasmonic THz detecter, the lesser *l*, the higher photoresponse can be obtained [12]. Moreover, in the other case of η_a= 100 where W_D = 10 μm and W_S= 0.1 μm (Fig. 5(c)) by increasing W_D while fixed W_S, photoresponse can be more enhanced than the reference (Fig. 5(a)) about 8 times as shown in Fig. 4. Because of the increase of C_{GD} by increasing W_D, the propagation distance (*l*) becomes shorter and the contrast of the electron density variation between estimated *l* and the other lower electron density region has also been enhanced. From these investigations with asymmetric FET structure, we can expect the more enhanced photoresponse by novel design of the plasmonic THz detectors with asymmetric source and drain structure.

IV. CONCLUSIONS

We have demonstrated that our novel methodology based on quasi-plasma 2DEG can provide the simulation framework for the structural design and analysis of Si FET-based nonresonant plasmonic THz detector. The asymmetric source and drain structure can be one of the key technologies for the enhanced photoresponse of the plasmonic THz detectors.

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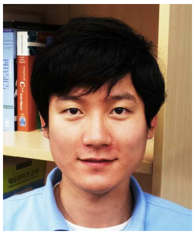

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