Monte Carlo Investigation of Silicon MOSFET for Terahertz Detection

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***Abstract*—In this paper, the terahertz (THz) detection based on Silicon MOSFET is investigated with two-dimensional (2D) ensemble Monte Carlo (MC) simulation study. The analytical model of responsivity to high frequency small signals based on the small-signal equivalent circuit of MOSFETs operating in terahertz detection mode are developed and calibrated. We explore the impacts of input excitation signals with different frequency and amplitude on THz detection. Moreover, it is shown that the responsivity to THz excitations could be controlled by modulation of the gate voltage and the gate length in the MOSFET.**

Keywords—Terahertz detection; Monte Carlo simulation; small-signal equivalent circuit; modulation

I. INTRODUCTION

Generation and detection of electromagnetic spectrum in the terahertz (THz) region is developing quickly for its potential applications in advanced technologies such as security, medical imaging, communications and quality assurance [1-3]. The plasmatic approach which exploits the plasma frequency associated with long range Coulomb interaction of charge carriers is one of the most promising strategies for THz generation/detection [4]. Previous work [5-8] has already shown the exploration of the THz generation and detection based on field-effect transistors (FETs) theoretically or experimentally. THz plasma oscillations based on the FET have been investigated with Monte Carlo (MC) method [9-11]. TCAD modeling and simulation of Silicon transistor for THz detection have been reported in [12-14].

However, a little work has been done to study the mechanism of the THz detection based on Silicon MOSFET and identify the effects of plasma resonances on THz detection. In this work, THz detection based on Si MOSFET is investigated with two-dimensional (2D) ensemble MC simulation study. We explore the impacts of input excitation signals with different frequency and amplitude on THz detection. Moreover, it is shown that the responsivity to the THz excitations could be modulated by the gate voltage and the gate length in Silicon MOSFET.

II. SIMULATION METHOD AND DEVICE STRUCTURE

A 2D full-band ensemble MC device simulator coupled with a 2D Poisson solver is used in our simulation [11, 15]. The band structure involves four conduction bands and three valence bands for silicon, one conduction band for silicon oxide. Scattering models such as phonon scattering model, impurity scattering model, impact ionization scattering model and surface roughness scattering model are considered in the simulator.

The schematic geometry of Silicon MOSFET operating in the THz detection mode is shown in Fig. 1. The sinusoidal signal of varying frequency is superimposed to the DC gate bias. The source contact is grounded and the induced drain to source voltage Vds is measured under zero drain current boundary condition. From the time series of instantaneous Vds values obtained from the MC simulation, we evaluate the responsivity to the THz excitations by Fourier transform of Vds fluctuations. The high frequency small-signal equivalent circuit model of MOSFET operating in THz detection mode is shown in Fig. 2. Based on the equivalent circuit, the analytical model of responsivity to high frequency small signal is developed by the circuit analysis for MC simulation verification. The default parameters used in this work are given in Table I. The gate length (Lg) is varying from 40 nm to 100 nm. The source and drain region (S/D) are 40 nm long and are assumed homogeneously doped with doping densities Ns/Nd 10^{20} cm^{-3}. The equivalent gate dielectric thickness is 1 nm.

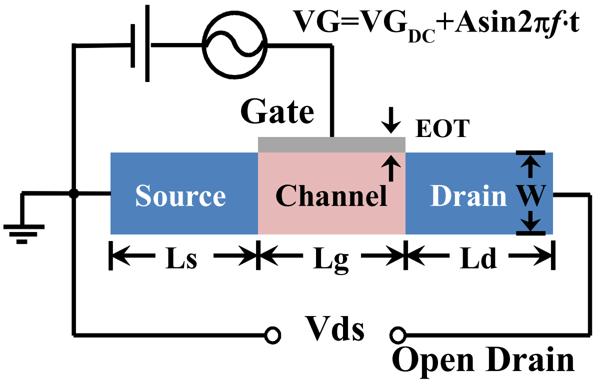

Fig. 1. Schematic geometry of a MOSFET operating in THz detection mode under open drain boundary condition.

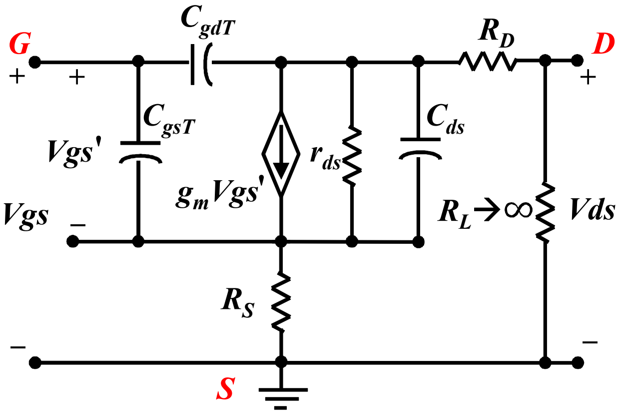

Fig. 2. Schematic geometry of a MOSFET operating in THz detection mode under open drain boundary condition.

TABLE I. DEFAULT PARAMETERS USED IN THIS WORK

Parameter	Description	Value
Lg	Gate Length	40-100nm
Ls/Ld	Source/Drain Length	40nm
W	Channel Thickness	20nm
Ns/Nd	Source/Drain Doping	10^{20} cm^{-3}
Nc	Channel Doping	10^{16} cm^{-3}
EOT	Equivalent Oxide Thickness	1nm

III. RESULTS AND DISCUSSION

Fig. 3 shows the input VG and the output response Vds for 2THz excitation in Lg=40nm MOSFET with MC quasi-continuous time domain simulation. By Fourier transform of the output response Vds fluctuations, the spectral density is presented in Fig. 4 and the responsivity to the 2THz excitation as well as the plasma frequency of the device can be observed.

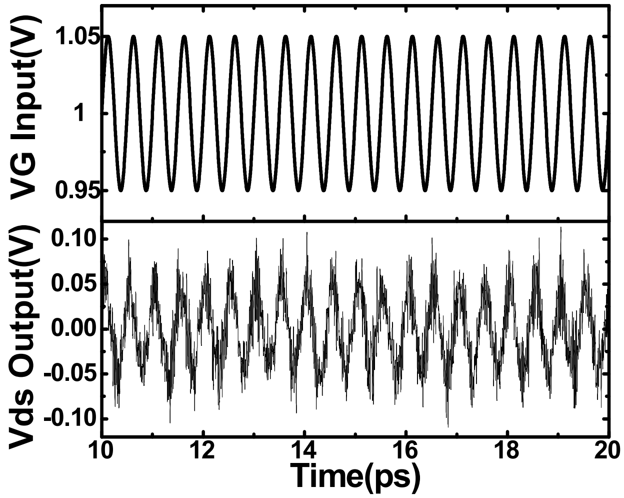

Fig. 3. VG input and Vds Output for 2THz excitation in Lg=40nm MOSFET with Monte Carlo quasi-continuous time domain simulation.

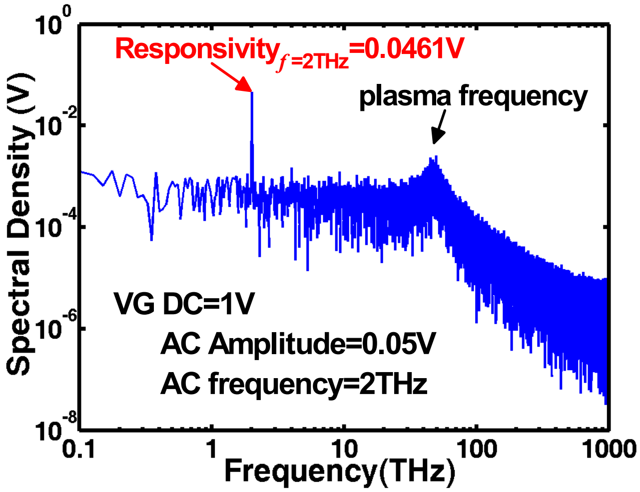

Fig. 4. The spectral density of Vds output for 2THz excitation at gate bias VG DC=1V, sinusoidal AC Amplitude=0.05V in Lg=40nm MOSFET.

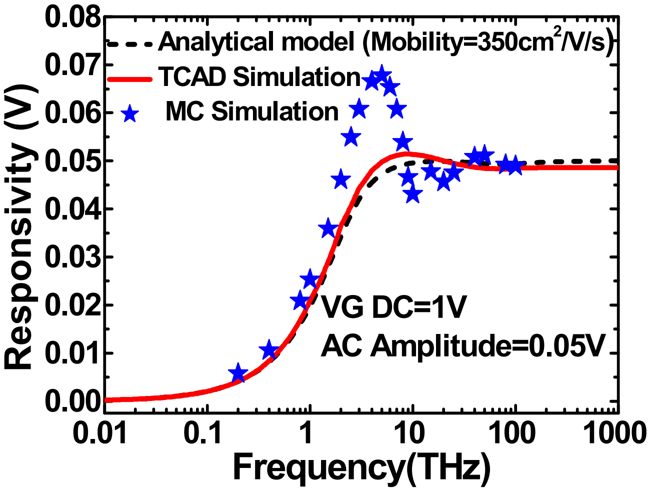

Fig. 5. Comparison of the responsivity to the different frequency excitation obtained from the analytical model, TCAD simulation and our Monte Carlo simulation.

Our previous studies have shown that the fluctuation in local carrier density coupling with local drift velocity fluctuation results in a fluctuant electric field by Poisson equation which feeds back into the Boltzmann transport equation and causes plasma oscillations [11].

We compare the responsivity to different frequency excitations of MC simulation with the analytical model of small-signal equivalent circuit and TCAD simulation in Fig. 5. The analytical model and TCAD simulation show good agreement with the MC results at low frequency. However, as observed, the responsivity shows a resonant peak around 5THz with the MC simulation method, which is due to the effects of plasma resonances. When the THz signal is coupled to the gate terminal, the responsivity mainly increases with the increased signal frequency.

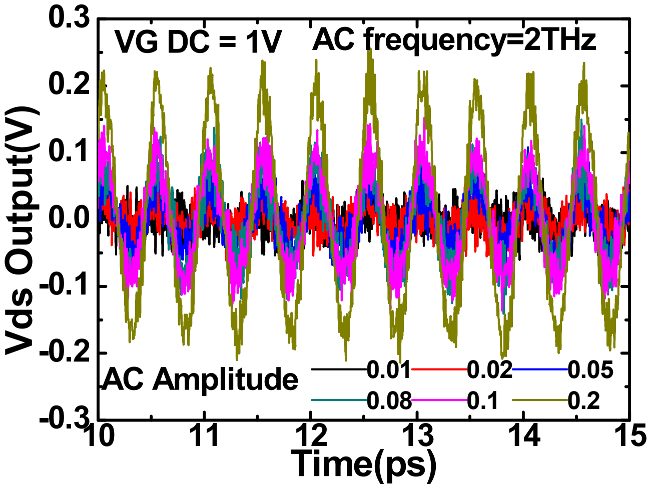

Fig.6. The instantaneous output response Vds for 2THz excitation at different sinusoidal signal amplitude in Lg=40nm MOSFET with Monte Carlo simulation.

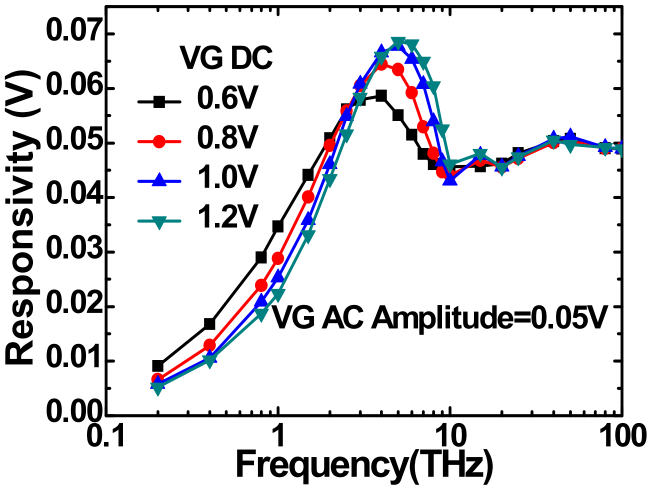

Fig.8. The responsivity to different frequency excitations at 0.05V sinusoidal signal amplitude under different DC gate biases in Lg=40nm MOSFET.

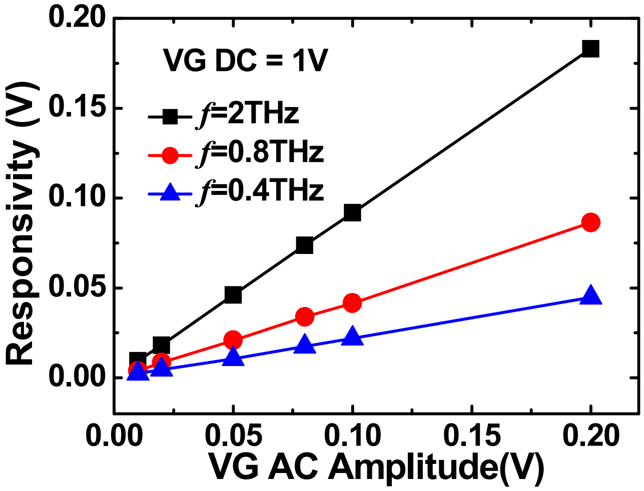

Fig.7. Dependence of sinusoidal signal amplitude on THz detection responsivity for 0.4THz, 0.8THz and 2THz excitations in Lg=40nm MOSFET.

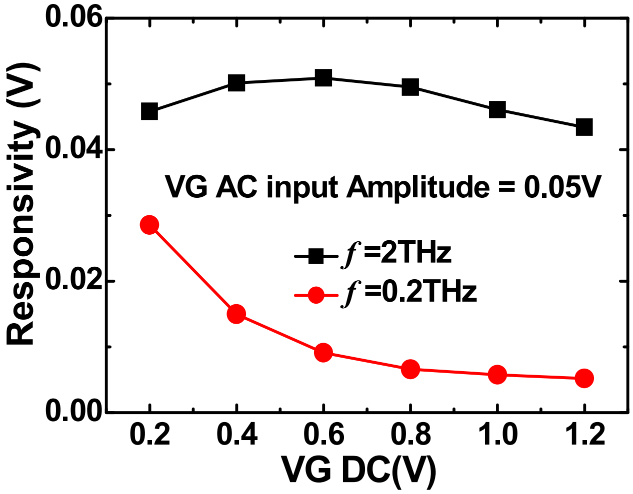

Fig.9. The responsivity to 0.2THz and 2THz excitations at 0.05V sinusoidal signal amplitude under different VG DC gate biases in Lg=40nm MOSFET.

Fig. 6 shows the instantaneous output response Vds for 2THz excitation with different sinusoidal amplitude in Lg=40nm MOSFET with Monte Carlo simulation. And the output response increases nearly linearly with the increased sinusoidal signal amplitude. Fig. 7 confirms the linear relation between the responsivity and the sinusoidal signal amplitude for 0.4, 0.8 and 2THz excitations. We further explore the responsivity to different frequency excitation under different DC gate biases in Fig. 8 and Fig. 9. Fig. 8 shows the responsivity to different frequency excitation at 0.05V sinusoidal signal amplitude under different DC gate biases in Lg=40nm MOSFET. Fig. 9 presents the responsivity to 0.2THz and 2THz excitation at 0.05V sinusoidal signal amplitude under different VG DC gate biases in Lg=40nm MOSFET. At lower frequency, the responsivity shifts towards lower values as Vgs increased, similar to experimental measurements [7]. On the contrary, the responsivity does not depend on the DC gate bias at higher frequency excitation.

The responsivity to different frequency excitation in different gate length MOSFET is also discussed in Fig. 10 and Fig. 11. The responsivity to different frequency excitations at VG DC=1V, AC Amplitude=0.05V in different gate length MOSFET is shown in Fig. 10. Fig. 11 presents the dependence of gate length in MOSFET on THz detection responsivity to different frequency excitations at VG DC=1V, AC Amplitude=0.05V. The resonant peak frequency is found to decrease for the increment of gate length, which is predicted in [5]. For lower frequency excitation, the responsivity increase slowly toward saturation with the increasing gate length, while the responsivity increase quickly toward saturation at high frequency, which agrees with the experiment [7].

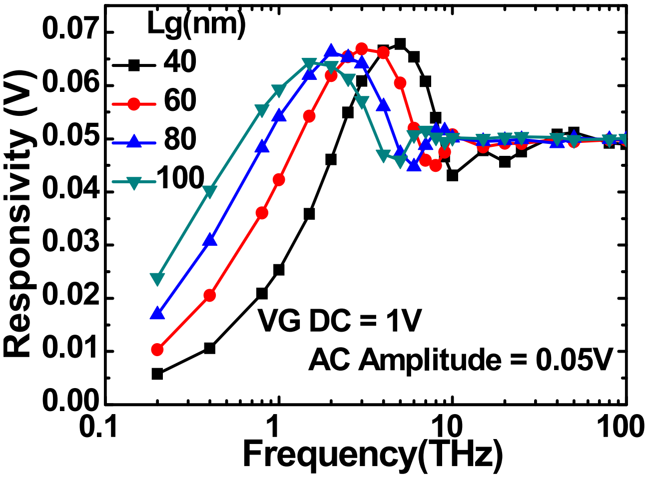

Fig.10. The responsivity to different frequency excitations at VG DC=1V, AC Amplitude=0.05V in different gate length MOSFET.

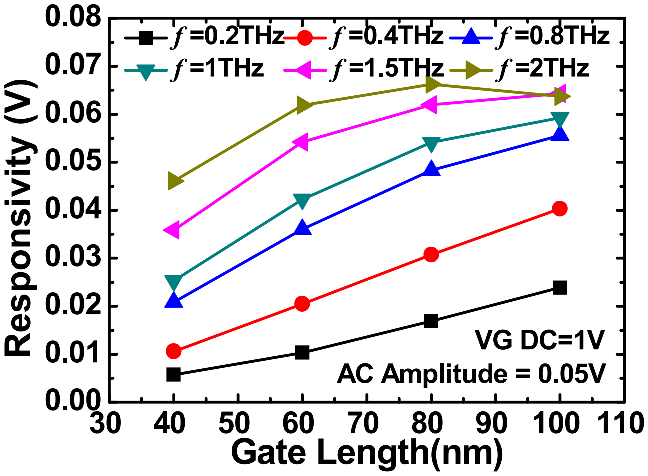

Fig.11. Dependence of gate length in MOSFET on THz detection responsivity to different frequency excitations at VG DC=1V, AC Amplitude=0.05V.

IV. CONCLUSIONS

In this paper, we present a Monte Carlo simulation study for THz detection based on Silicon MOSFET. The impacts of input excitation signals with different frequency and amplitude on THz detection have been explored. What's more, we show the effects of plasma resonances on the THz detection and that the resonant peak and the responsivity to THz excitations could be modulated by gate voltages and gate length in the MOSFET.

ACKNOWLEDGMENT

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