Demonstration of 2.58 THz detectors based on asymmetric channel transistors
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Abstract This letter presents several antenna-coupled 2.58 THz direct detectors based on 55 nm standard CMOS process. Each detector consists of a patch antenna and a metal-oxide-semiconductor field-effect-transistor (MOSFET) with an asymmetric channel. We demonstrated four detectors with THz wave coupling into the source with different width ratios of drain and source, and found that the responsivity is proportional to its asymmetric ratio. The detectors’ output signal is amplified with a low noise amplifier and extracted with a lock-in amplifier. The measured results showed that 2.58 THz detectors has a maximum responsivity (R_m) of 822.5 V/W, with a corresponding noise equivalent power (NEP) of 24.2 pW/Hz^{1/2}.

key words: Asymmetric channel, detectors, drain, field effect transistors, source, THz.

Classification: THz devices, circuits and modules

1. Introduction

The THz technology[1] witnesses increasing developments in various applications such as security checking[2-6], medical or biological imaging[7-9], radio astronomy[10-12], material analysis[13-14], and wireless communication[15]. The reason why THz imaging has achieved a rapid development is due to its unique properties and the appearance of high power terahertz sources[16].

Field effect transistor based incoherent (direct) terahertz detectors has been developed and applied widely in terahertz imaging for a few decades owing to its relatively high response to THz signal with the rectification of the RF input signal. Besides, CMOS fabrication processes provide a low cost and high compatibility solution for the implementation of large scale focal plane arrays. There have been lots of works on MOSFET detectors imaging[17-21] based on plasma wave theory[22-24], resistive mixing and distributed resistive self-mixing[25-26]. Based on an antenna-coupled detector structure, lots of works have been done to improve both the performance and the system cost. However, there have been very few works targeting on the shape of FET channels.

In this letter, we present four MOSFET detectors with asymmetric channels, which mainly differs in their widths of source and drain. These differences exert significant influence on these detectors’ performance.

2. Rectification in a transistor channel

To better understand the mixing process in a transistor channel, resistive self-mixing has been proposed to describe the internal physical phenomenon which can be analyzed by two essentially the same methods: the resistive self-mixing method (quasi-static analysis for low frequencies) and the distributed resistive mixing (nonequasi-static analysis for high frequencies). The transistor channel rectifies the RF or THz input signal to a DC voltage or current ready to be readout. Under both circumstances, the DC current after the channel rectification can be written as[26]

\[ I_{ds} = \frac{W}{L} \mu C_{ox} V_{RF}^2 / 4 \]

where the W and L are the width and length of the transistor channel, \( \mu \) is the mobility of the electron, \( C_{ox} \) is the oxide capacitance per unit area, \( V_{RF} \) is the amplitude of a time harmonic AC input signal \( V_{RF} = V_{Resin(\omega t)} \).

As for the voltage readout mode, we can obtain the output voltage by considering the DC conductance \( G_{ds} \) (\( G_{ds} = W/L \mu C_{ox} (V_{c} V_{ds}) \)) of the channel as[26]

\[ V_{ds} = \frac{I_{ds}}{G_{ds}} = \frac{V_{RF}^2}{4(V_{g} - V_{th})} \]

\( V_{g} \) is the gate bias and \( V_{th} \) is threshold voltage.

For the source-coupled detector in Fig.1, the gate to channel parasitic capacitor \( C_{gc} \) has a significant influence on the response to THz AC signal. This \( C_{gc} \) can be described by a gate to source capacitor \( C_{gs} \) and a gate to drain capacitor \( C_{gd} \). The efficient mixing process only takes place near the source terminal[26], in other words, most of the electrons will gather near the source terminal. Increasing the gate to source impedance \( Z_{gs} \) or decreasing the gate to drain impedance \( Z_{gd} \) should induce a higher response[27].
According to the impedance calculation, designers should try to decrease the gate to source capacitor $C_{gs}$ or increase the gate to drain capacitor $C_{gd}$ to achieve a higher response. And the simplest way to obtain a smaller $C_{gs}$ is to fabricate a transistor with a small source or larger drain. Thus we have designed three transistors with different sizes and a large source one for comparison shown in section 3.

3. Design of direct detectors

Instead of using the most commonly differential configuration detector in [28], we resort to a single transistor source-coupled detector [29] which is able to collect almost all the power that the antenna receives to achieve a higher response. Fig. 1 shows the schematic of this detector including a patch antenna to capture the THz wave, a MOSFET to detect the THz signal and a quarter of wavelength transmission line to eliminate the impedance mismatch between the antenna and the source of the transistor to obtain a maximum power transfer efficiency.

Fig. 1. Schematic of the single transistor source-coupled detector.

3.1 Microstrip patch antenna

As shown in Fig. 2, the patch antenna was implemented using the 10.335μm nine metal layers. The antenna receives the THz wave from the high power Quantum Cascade Laser (QCL) terahertz source, and then transmits this AC signal to the detector’s source. The antenna uses the bottom layer (0.22μm) as the ground layer, and adopts the second to top layer (3.35μm) as the radiation patch. Both the length $L_G$ and width $W_G$ of the ground are set as 30μm to prevent the leakage of the electromagnetic wave. The radiation patch has a length $L_P$ of 30μm and a width $W_P$ of 23μm. The feeding line’s length $L_M$ and width $W_M$ are 13.5μm and 1.5μm, respectively.

Fig. 2. Simplified model of the patch antenna.

The center of the patch is connected to the ground plane to obtain a zero-field point and thus it can be connected to other interconnections without impacting the antenna electromagnetic performance.

3.2 Asymmetric channel transistor

Only a few works [27] addressing the shape of MOSFET channel of terahertz detectors transistors have been reported recently.

Fig. 3 shows the detector transistors with a T-type asymmetric channel. Referenced by this architecture, we performed other three asymmetric transistor with different width of source and drain of the left and one of the right at 2.58THz.

Fig. 3. Transistor with asymmetric channel, left: narrow source, right: wide source.

Specifically, the length of the channel is $L=0.32μm$, the width of the active region next to the drain and source are $W_D$ and $W_S$, respectively, and the ratio of $W_D$ and $W_S$ is $\eta$, $\eta=W_D/W_S$. We fixed $W_S$ as 0.12μm and altered $W_D$ of narrow source detectors as 0.12μm, 0.24μm, 0.48μm (corresponding to $\eta=1, 2, 4$, respectively). While in the wide source detector, we set $W_S=0.48μm$, $W_D=0.12μm$, hence $\eta=1/4$. Based on these transistors, we adopted the simplest antenna-coupled detector structure in Fig. 1. Besides, we could not use the smallest size of the transistor since its fabrication process (i.e., the standard 55 nm) is restricted by design rules.

Fig. 4. Die micrograph of the all the detectors.

4. Measurement setup and results

The detectors in this work are implemented by Global Foundry 55 nm standard fabrication process. Fig. 4 shows the die micrograph of all the 46 detectors. This work only involves four of them and the others are presented elsewhere.
Fig. 5. Block diagram of the output voltage measurement setup.

Fig. 5 shows the measurement setup for the detector’s output. A QCL source has a wave beam diameter of 500μm and transmits an average power of 60mW terahertz wave with a 4% duty cycle in free space. Then the terahertz wave was collimated and focused by two parabolic mirrors onto the detectors. The detector chip was bonded onto an FR-4 printed circuit board (PCB). Moreover, the output signal of the detector was connected to a voltage gain of 60dB SR560 low noise voltage amplifier and then extracted by a SR830 lock-in amplifier.

Fig. 6 shows the simulated return loss (-S11) curve of the 2.58THz patch antenna, which shows that this THz antenna has a band width of 130GHz from 2.54THz to 2.67THz below -10dB.

Fig. 6. Simulated S11 of the 2.58THz antenna.

Fig. 7 shows the simulated radiation pattern of the antenna indicating that the antenna has a good directivity in Z axis. Thus we must keep THz wave incident onto the antenna in a normal direction. The simulated gain G and radiation efficiency are 5.4dBi and 77.9% respectively which makes the calculated $A_{eff} = 5.78 \times 10^3 \mu m^2$.

The responsivity of a detector is defined as the ratio of the output voltage or current to the incident power that the antenna receives. In this work, we achieved the voltage responsivity, $R_V$, and it can be expressed as follows[29]:

$$R_V = \frac{U_{out}}{P_{in}} = \frac{U_{out}}{J_{in} A_{eff}}$$

(3)

where $U_{out}$ is the output voltage obtained by calculating the lock-in amplifier output, $P_{in}$ is the THz wave power the antenna received, $J_{in}$ is the THz power density which the antenna received, and $A_{eff}$ is the effective area of the on-chip antenna, $A_{eff} = D^2/4\pi$, $D$ is the directivity of the antenna, $\lambda$ is the electromagnetic wavelength at certain frequency. However, when taking radiation loss into consideration, we used $G$ to replace $D$. We avoided applying the gate bias to the transistor due to the uncertainty of the working conditions.

Fig. 7. Simulated radiation pattern of the antenna.

Fig. 8. Measured and simulated results of the narrow source detector.

The simulated and measured results for the narrow source transistor detectors are plotted in Fig. 8. We increased the asymmetric ratio by increasing the $C_{pd}$ of the transistor model of [27] when obtaining the simulation results, it exhibited that the responsivity is improved as the asymmetric ratio increases and the measured results agree well with the simulated ones. Particularly, the maximum responsivity of the narrow source asymmetric detector is 365.2V/W. Interestingly, it is more than a half smaller than 822.5V/W of the wide source detector. First of all, the asymmetry still exists
and it is in a reverse way contrary to the narrow source detector. Besides, although the mixing only takes place near the source terminal, the channel is connected as a whole. The DC current has to flow through the whole channel, thus $Z_{ds}$ and $Z_{gd}$ will simultaneously affect the total DC voltage of the channel. Last but not least, wider source can collect more electrons which naturally has a larger $I_{ds}$. Therefore when multiplying $Z_{ds}$ and $Z_{gd}$, we can achieve a higher $V_{ds}$.

NEP is defined as the input power which results in the unity signal-noise-ratio (SNR) across 1 Hz bandwidth and it is formulated as[26]:

$$\text{NEP} = \sqrt{\frac{N_0}{R_V}} = \sqrt{\frac{kT R_{ch}}{R_V}}$$

where $N_0=4k_B T R_{ch}$ is the noise power spectral density, which is only determined by the thermal noise of the channel resistor $R_{ch}$. According to the measured responsivity, the minimum NEP of the detectors is 24.2 pW/Hz$^{0.5}$ for the wide source detector.

5. Conclusion

We present four 2.58 THz antenna coupled detectors with asymmetric channel transistors based on 55 nm standard CMOS process. With a voltage gain of 60 dB LNA and a lock-in amplifier, the highest responsivity reaches 822.5 V/W, and the minimum NEP reaches 24.2 pW/Hz$^{0.5}$. The responsivity of a narrow source detector improves as the asymmetric ratio becomes larger. To emphasize, due to the charge asymmetry in the channel, a wide source detector may acquire relatively high responsivity, which renders the possibility of achieving an ultra-high responsivity if private fabrication process could be adopted.

Acknowledgements

This work was supported by the National Key R&D Program of China (2016YFA0202200), AoShan Talents outstanding scientist Program Supported by Pilot National Laboratory for Marine Science and Technology (Qingdao) (No. 2017ASTCP-OS03), and the leading talents of Guangdong province program under grant 2016J06D557.

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