第 37 卷第 4 期
2018 年 8 月

红 外 与 毫 米 波 学 报
J. Infrared Millim. Waves

Vol. 37, No. 4
August, 2018

文章编号: 1001 - 9014(2018)04 - 0389 - 04

DOI: 10.11972/j.issn.1001 - 9014.2018.04.002

An effective method for antenna design in field effect transistor terahertz detectors

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Abstract: In the implementation of field effect transistor (FET) terahertz (THz) detectors, the integration of properly designed planar antennas could effectively enhance the coupling efficiencies between the transistors and THz radiation, thus improving the responsivities of THz detectors. A method to design the planar antenna which is based on the simulation of channel electric field at the gate edge of FET is reported here. This method is suitable for the situation where the input impedances of FETs may not be conveniently obtained in the THz regime. The validity of this method in the antenna design is confirmed by the measurements of the fabricated GaN/AlGaN FET THz detectors. The maximum responsivities of the bowtie detector and the dual-dipole detector are obtained at 170.7 GHz (1 568.4 V/W) and 124.3 GHz (1 047.2 V/W) respectively, which are close to the simulation results of channel electric field at the gate edge of the bowtie detector and the dual-dipole detector.

Key words: terahertz detectors, planar antenna, channel electric field, field effect transistors
PACS: 07.57.Kp, 84.40.Ba, 85.30.Tv, 81.05.Ea

基于场效应晶体管的太赫兹探测器中天线设计的一种有效方法

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Received date: 2017-11-29, **revised date**: 2018-03-07　　**收稿日期**:2017-11-29, **修回日期**:2018-03-07

Foundation items: Supported by National Natural Science Foundation of China (61501421), the National Key R&D program of China (2016YFA02005003), the One Hundred Talents Program of Chinese Academy of Sciences (Y673010000), the Chinese Academy of Sciences Project (Y6JA061001), the National Science Centre, Poland through the Sonata BIS project (2016/22/E/ST7/00526), and the Foundation for Polish Science through the TEAM project (TEAM/2016-3/25)

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摘要：在场效应晶体管太赫兹探测器中，合理的天线设计可以增强晶体管和太赫兹波之间的耦合效率，从而提高太赫兹探测器的响应度. 提出一种基于晶体管栅极边缘沟道电场的仿真来设计平面天线的方法. 这种方法尤其适用于太赫兹波段晶体管输入阻抗不容易得到的情况. 通过流片完成的基于氮化镓高电子迁移率晶体管的太赫兹探测器的响应度测试证实了这种方法的有效性. 集成碟形天线和双偶极子天线的太赫兹探测器最大响应度分别在170.7 GHz (1568.4 V/W)和124.3 GHz (1047.2 V/W)频点处测得，这个测试结果接近基于晶体管栅极边缘沟道电场的仿真结果.

关 键 词：太赫兹探测器；平面天线；沟道电场；场效应晶体管

中图分类号：TN386 **文献标识码：**A

Introduction

In recent years, the terahertz (THz) technology has attracted increasing attention on account of its broad applications in biomedical testing, security imaging, environmental monitoring, radar, and communications[1-2]. With the advantages of compactness, fast response, high sensitivity, and room temperature operation, the field effect transistor (FET) THz detector has become one of the most promising semiconductor THz detectors. The theory of THz detection by FETs considering electron plasma oscillations in the transistor channel was first presented by Dyakonov and Shur in early 1 990s[3-4]. Since then, numerous FET THz detectors have been fabricated and investigated[5]. Meanwhile, THz imaging has also achieved a considerable progress[6].

However, in many cases the responsivities of FET THz detectors are still far from theoretically predicted level. One of the main problems is the low coupling efficiency between the transistor and the incident radiation. Many researchers chose to integrate some types of planar antennas on the transistors to enhance the coupling efficiencies. These planar antennas include patch antenna[7], bowtie antenna[8], trip resonant antenna[9], floating antenna[10], and novel nanoantennas[11]. It has been demonstrated that most of these antennas can enhance the detector responsivities to some extent. However, a proper method to design the antenna and optimize its receiving characteristics at desired frequency is still lacking. Here, we propose a method to design the planar antenna, which is based on the simulation of channel electric field at the gate edge of FET. This method is especially suitable for the situation where the FET input impedances may not be conveniently determined, which is often the case in the THz range. We demonstrate efficiency of this method by comparing simulations with results of THz responsivity experiments on in purpose fabricated GaN/AlGaN FET THz detectors.

1 Design method

In the implementation of FET THz detectors, the planar antennas are used as receiving antennas coupling the external radiation to the transistors. According to the reciprocity theory[12], the antenna properties of receiving and radiating modes should be the same. In consequence, with currently available commercial simulators, the simulations in the radiating mode are usually performed for convenience. In general, the design of planar antennas is based on the electromagnetic simulation of the S_{11} parameter. However, the S_{11} parameter is obviously influenced by the antenna source impedance. In the design, two terminals of the antenna are usually connected to the gate and source electrodes of FET respectively. Hence, the transistor input impedance can be regarded as antenna source impedance in the simulation. In the range of THz frequency, although the accurate transistor input impedances are possible to be obtained, it still needs expensive test devices and complicated process. Therefore, we propose a new method to design planar antennas of FET THz detectors. This new method is based on the assumption that in the receiving mode, it is the electric field between two pieces of a dipole antenna that is associated with the detector responsivity. This assumption is based on the self-mixing theory for THz detection[9-10] which effectively predicts that the responsivity is closely related with the electric field induced at the gate edge of FET. Although the responsivity is also influenced by other factors such as device parasitic parameters[13] and substrate effect[14], we only pay attention to antenna design here and keep others the same. As a result, we propose to design planar antenna on the basis of the simulated channel electric field at the gate edge of FET.

2 Simulation of antennas

The simulation considered here is an actual schematic of a THz detector based on a GaN high electron mobility transistor (HEMT) which was fabricated in our laboratory. The simulation structure consists of a finite slab substrate with pads, planar antenna, and HEMT situated on the top surface. The substrate contains several layers as shown in Fig. 1. The length and width of the substrate are both 1 mm. From our previous study[14], the substrate thickness is optimized to be ~179 μm. We choose two types of planar antennas (bowtie and dual-dipole) in the simulation. The dimensions of the top structures are shown in Fig. 2 (a) and (b), and they are made of two metal layers (200 nm Au layer on the top and 20 nm Ni layer on the bottom). In addition, FET THz detectors are usually working near the threshold value of gate voltage where the channel is almost pinched off. Under such condition, the channel conductivity can be neglected. This is the reason why we choose the combination of lossless semiconductor materials to simulate the HEMT. In our simulation, a plane wave with scanning frequency is used to illuminate the structure. The wave vector of the incident wave is perpendicular to the surface of the antenna, while the polarization direction is parallel to the long axis of the antenna (the Y axis in

Fig. 2 (a) and (b)). The magnitude of electric field of the incident THz wave is kept at 1 V/m. We choose the commercial program COMSOL using the finite element method (FEM) to simulate those structures.

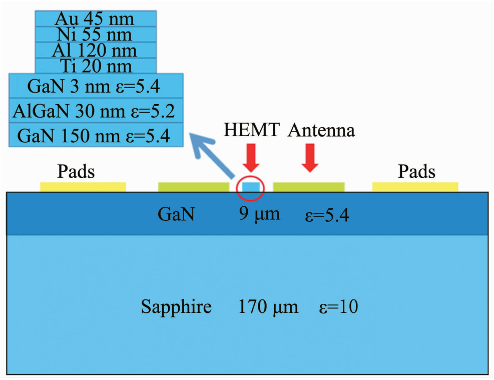

Fig. 1 The schematic cross section of the THz detector. The relative dielectric constant of each layer is represented by ε
图 1 太赫兹探测器模型横截面示意图. 每一层材料的相对介电常数用 ε 表示

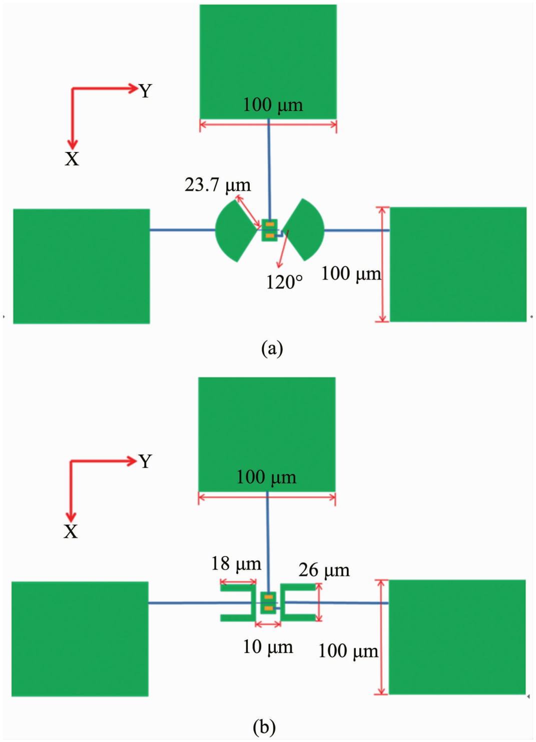

Fig. 2 The whole structure in simulation from top view. (a) The bowtie antenna with pads & HEMT, (b) the dual-dipole antenna with pads & HEMT
图 2 仿真中全部上表面结构的俯视图(a)包含焊盘和晶体管的碟形天线,(b)包含焊盘和晶体管的双偶极子天线

In the simulation, we try to identify the resonant frequencies of different antennas in terms of the maximum channel electric field at the gate edge of HEMT in the receiving mode. From the simulation results of the whole structures, as shown in Fig. 3, the maximum electric field of bowtie antenna is obtained at 175 GHz, while that of dual-dipole antenna is obtained at 120 GHz. Besides, the maximum electric field of bowtie antenna is approximately 1.5 times as large as that of dual-dipole antenna. One can see that compared with the structure only including pads & HEMT, the bowtie antenna can enhance the electric field at 175 GHz, while the dual-dipole antenna only changes the resonant frequency without any enhancement. As a result, the resonant frequency of the bowtie detector is 175 GHz, while that of the dual-dipole detector is 120 GHz.

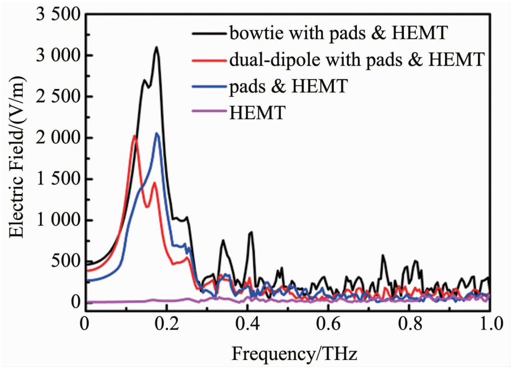

Fig. 3 The simulated channel electric field of several structures versus frequency
图 3 多个结构仿真得到的沟道电场随频率变化关系

3 Experiments and results

The device is fabricated on a GaN/AlGaN HEMT, which provides a two-dimensional electron gas (2DEG) about 33 nm below the surface. At 300 K, the electron mobility is 1 650 $\mathrm{cm}^2/\mathrm{Vs}$ and the electron density is $4.5\times10^{12}\ \mathrm{cm}^{-2}$. The device fabrication started with mesa isolation by inductively coupled plasma (ICP) etching. Source and drain ohmic contacts were formed by Ti/Al/Ni/Au (20/120/55/45 nm) electron-beam deposition followed by 400/700/870 °C rapid thermal annealing in N_2 ambient. The gate and planar antenna were made of Ni/Au (20/200 nm) using electron-beam lithography and lift-off process. Then, 20/200 nm thick Ni/Au bonding pads (100 μm × 100 μm) were deposited. Finally, the substrate thickness was thinned to around 180 μm which is corresponding to the substrate thickness in our simulation. The scanning electron microscopy (SEM) images of GaN HEMT of the THz detector are shown in Fig. 4 (a) and (b). The gate length of HEMT is 134 nm. The source-drain distance is 2.607 μm. The

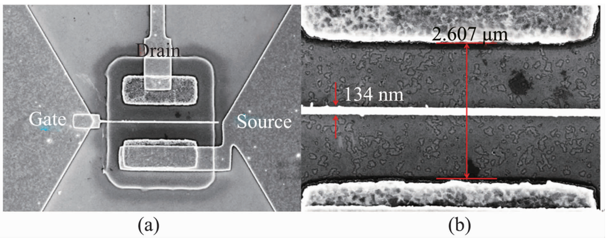

Fig. 4 (a) The SEM image of GaN HEMT of the THz detector, (b) the detail between the source and drain electrode
图 4 (a)太赫兹探测器中氮化镓高电子迁移率晶体管部分的扫描电镜照片,(b)源漏极之间的细节

dimensions of whole structures in fabrication are consistent with those in simulation.

The detectors were characterized using the lock-in technique in the frequency range 110 ~ 440 GHz at room temperature. We used several broadband electrically tunable solid state THz sources in our measurements. The off-axis parabolic mirrors were used to focus the incident radiation to around 1.5 mm diameter spot. The electric field of THz radiation was directed along the long axis of the antennas. All measurements were done with 1 MΩ load resistor without amplification. The modulation frequency of the mechanical chopper was 234 Hz.

The measured respon-sivities as a function of frequency for GaN HEMT THz detectors integrated with bowtie and dual-dipole antennas are plotted in Fig. 5. We also put the simulated electric field in the same figure for comparison. From the figure, the maximum responsivity (1 568.4 V/W) of the bowtie detector is obtained at 170.7 GHz, while that (1 047.2 V/W) of the dual-dipole detector is at 124.3 GHz. The maximum responsivity of the bowtie detector is approximately 1.5 times as large as that of the dual-dipole detector. As for the difference in bandwidth between simulation and experiment, it may relate to the accurate values of relative dielectric constants in the terahertz range. When the actual dielectric constants deviate from the set values in simulation, the changed effective wavelength would influence the coupling efficiencies between the antenna and THz radiation, thus decreasing the measured responsivities at some frequencies. On the whole, the measured results are close to the simulation results of channel electric field at the gate edge of HEMT. Therefore, we can draw the conclusion that the channel electric field at the gate edge is an effective reference to design planar antennas for FET THz detectors. This method is feasible to identify the resonant frequencies and predict the performances of FET THz detectors, especially for the situation in which the input impedances of FETs may not be conveniently obtained in the THz regime.

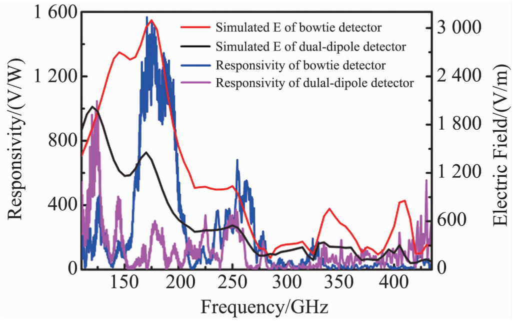

Fig. 5 The measured responsivities as a function of frequency for THz detectors integrated with bowtie and dual-dipole antennas

图 5 集成碟形天线和双偶极子天线的太赫兹探测器测量得到的响应度随频率的变化关系

4 Conclusions

In conclusion, we have proposed a method to identify the resonant frequencies and evaluate the performances of different antennas for FET THz detectors on the basis of the simulated channel electric field at the gate edge. This method is especially suitable for the situation where the input impedances of FETs may not be conveniently determined in the THz regime. Through the fabrication and measurement, the maximum responsivities of the bowtie detector and the dual-dipole detector are obtained at 170.7 GHz and 124.3 GHz respectively. And the maximum responsivity (1 568.4 V/W) of the bowtie detector is approximately 1.5 times as large as that (1 047.2 V/W) of the dual-dipole detector. Those results are close to the simulation results of channel electric field at the gate edge of the bowtie detector and the dual-dipole detector. Therefore, this method has been experimentally confirmed, indicating its validity in the antenna design of FET THz detectors. We hope this proposed method will shed light on the antenna design of FET THz detectors.

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